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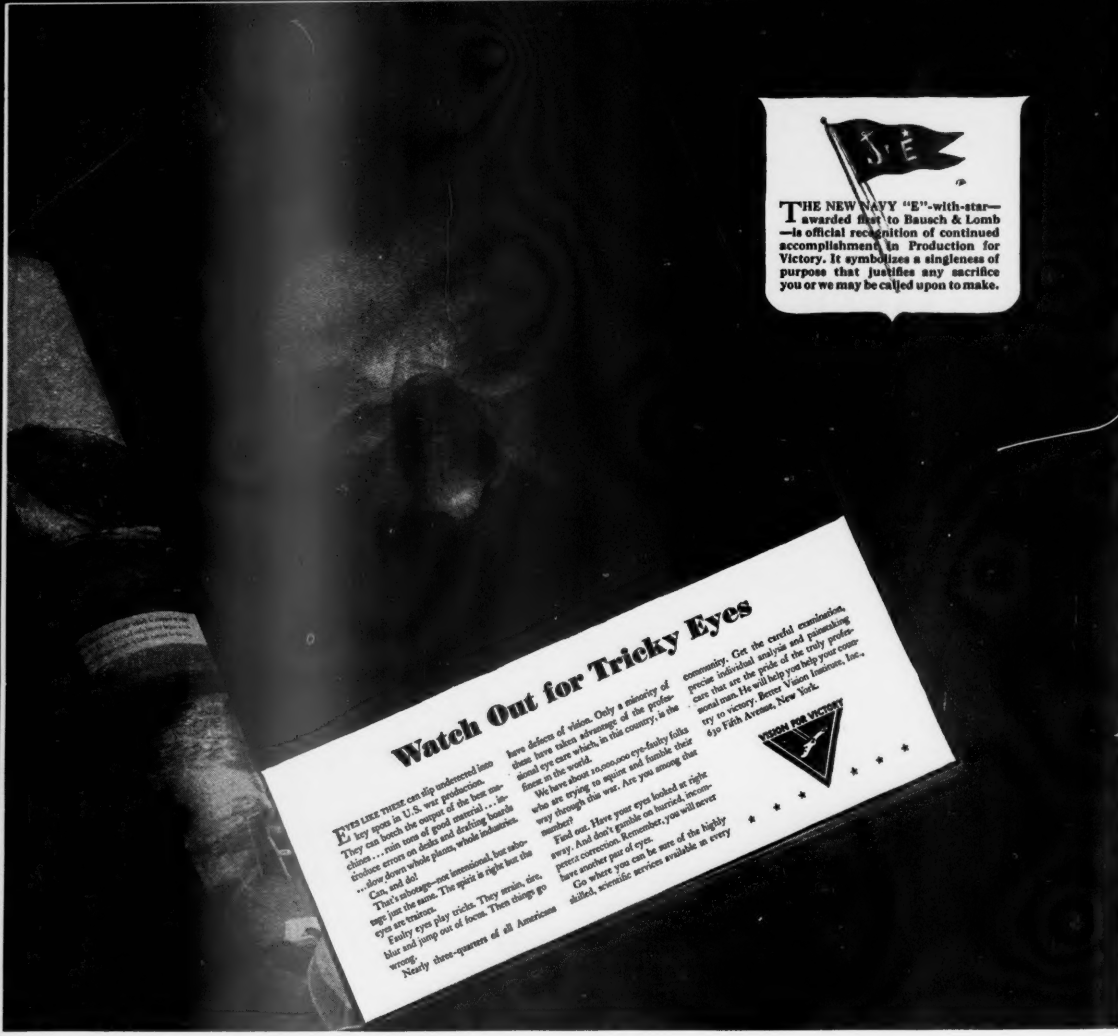

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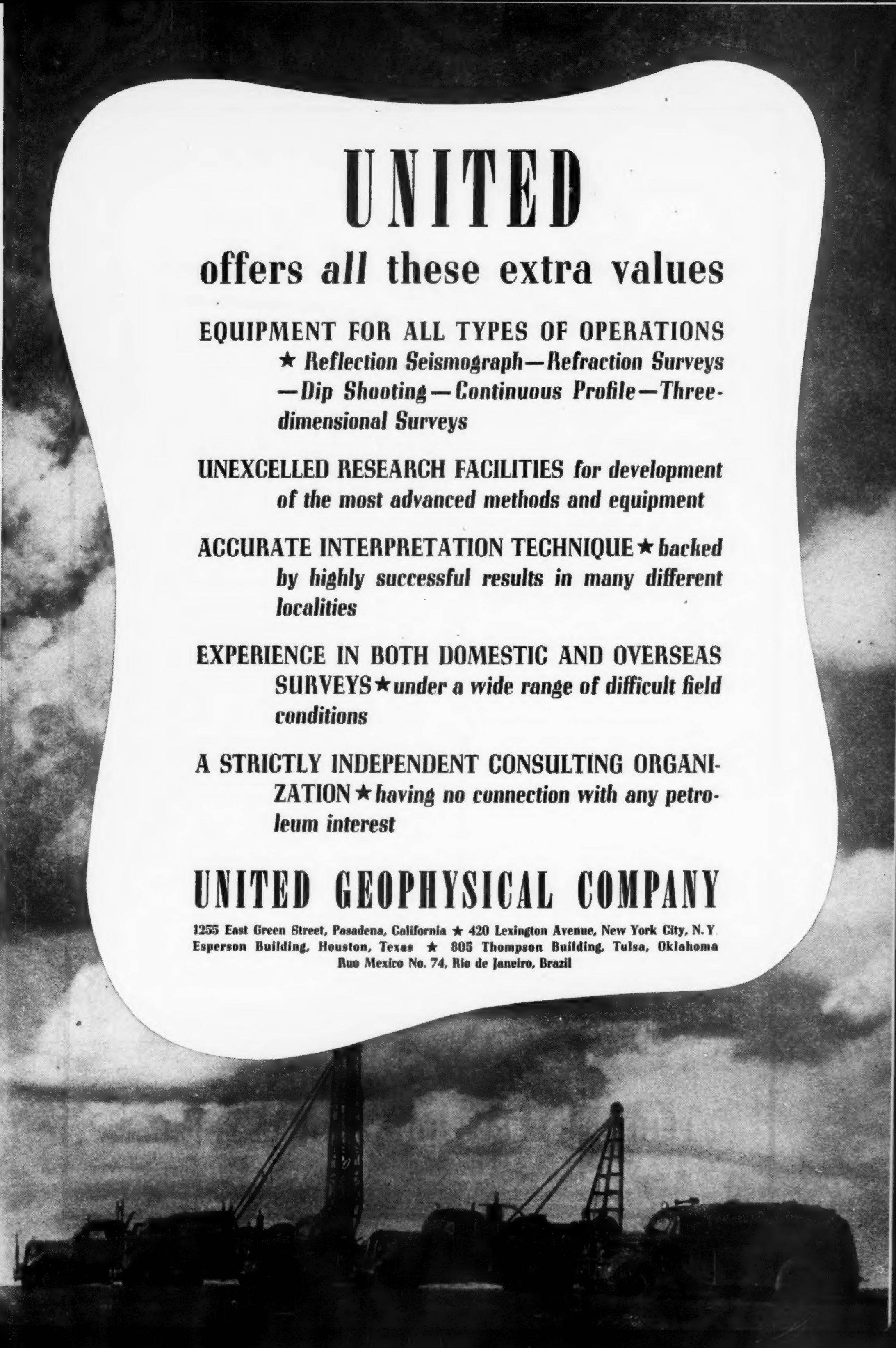
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BULLETIN
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NOVEMBER, 1942

STRATIGRAPHICAL ANALYSIS AND ENVIRONMENTAL RECONSTRUCTION[1]

THOMAS G. PAYNE[2]
Chicago, Illinois

ABSTRACT

This paper presents a plan for comprehensive study and analysis of a sedimentary deposit, including petrographic and paleontologic description of the fundamental attributes, properties, and structures of the sediment and its life assemblage and the interpretive description of genesis of the deposit. The genetic phase embraces evaluation of the environmental factors, ecologic and geographic, and the dynamic processes and resultants involved in sedimentary petrogenesis. Methods, principles and concepts are illustrated throughout the paper by use of the crinoidal phase (Bed 9) of the Grand Tower limestone of Ste. Genevieve County, southeastern Missouri, as a test case.

I. Introduction

Paleoecology.—With the exception of relatively small areas of bare rock and artificial structures, the subaerial and subaqueous surface of the earth constitutes a life-sediment sphere. In this sphere living organisms and sediments are not only coexistent and interrelated but are influenced to different degrees by the same set of environmental factors. The term *ecology*, in its broadest connotation, may be applied to the environmental relationships of organisms and of the sediments with which they are associated.

Paleoecology, both organic and sedimentary, is a fertile field for geologic research. It is coming to be realized that the life and rock records must be interpreted from the environmental viewpoint, utilizing the ever-expanding background of knowledge of recent sediments and organisms. At present many earth historians have become so bogged down in their own mire of formations, correlation charts, species, controversies, and the like that some of the more fundamental issues have been sidetracked. It is often forgotten that stratigraphic classifications, correlation charts, and faunal lists are not ends in themselves but are rather means to an end, an end that should recreate and picture the organic and physical earth throughout the flow of geologic time.

Stratigraphic analysis.—If stratigraphy is ever to become much more than a "library" science, its exponents must concern themselves less with problems of arbitrary stratigraphic classification and nomenclature and more with funda-

[1] Submitted as a Ph.D. thesis, University of Chicago, Chicago, Illinois, September, 1941. Manuscript received, April 3, 1942.

[2] Present address: Kansas State Geological Survey, Lawrence, Kansas.

mental lithologic description and classification, less with problems involving the correlation of strata hundreds of miles apart and more with the interpretive analysis of the environmental settings represented by the fundamental rock types. Stratigraphic classification, nomenclature, and correlation are important but never will be accomplished satisfactorily until the rocks themselves and the environments which they represent are described and understood—and we are far from such an understanding at the present time.

The literature of stratigraphy is characterized by superficial lithologic descriptions—field descriptions which have served their immediate purpose but have failed to lead the way to a rigorous understanding of the stratigraphic record. The past twenty years have brought forth detailed studies in the field of sedimentary petrology, studies which have been mathematically rigorous in their methods and logical in their approach, but they too have failed in certain respects, namely, that they have been highly specialized and restricted in scope and too time-consuming for widespread stratigraphic application.

Recent petrologic work has paved the way but has not as yet led to and provided a plan for comprehensive analysis and understanding of a sedimentary rock. Rather than considering a sedimentary assemblage in the light of the whole, recent studies have treated only certain sedimentary attributes and properties and have been concerned only with individual, isolated approaches, such as insoluble-residue studies, heavy-mineral analyses, size or shape analyses, porosity determinations, studies of structures, and so forth. Environmental interpretations have been random and inconclusive. The whole story has been told for only few sedimentary deposits, but partial pictures have been presented for many. One notable exception is Krynine's comprehensive and classic treatment of the "Petrology and Genesis of the Third Bradford Sand."[3]

It is now coming to be realized that the future must bring a new form of stratigraphic research, middle-road research which will bridge the gap between the *old stratigraphy* and the *new stratigraphy* that is now unfolding. This middle-road policy will call for complete restudy of the stratigraphic record and for lithologic descriptions and environmental interpretations which recognize and evaluate in a simple semi-quantitative manner the fundamental attributes, properties, and structures of a sediment and the environmental factors and sedimentational processes which control its genesis. With stratigraphic or sedimentary traps becoming of increasing importance in petroleum exploration, the new stratigraphy with its lithologic and environmental research must undergo rapid growth in the near future.

North American Paleozoic rocks are characterized by recurrence in time and space of certain fundamental lithologic and environmental types. It would seem that Werner's medieval concept of "universal formations" might well be revived and altered to a concept of "universal lithologic types." The new stratigraphy

[3] P. Krynine, "Petrology and Genesis of the Third Bradford Sand," *Pennsylvania State College Bull. 29* (1940), pp. 1–134.

must include a breakdown of the stratigraphic record into lithologic and environmental types and their varieties and must place emphasis on *lithologic classification* as well as stratigraphic classification.

The present paper.—This contribution represents an attempt to devise a logical and orderly plan for rapid but rigorous analysis of the sedimentary record. The procedure set forth and illustrated in this paper is tentative in nature, and it is hoped that interested persons will contribute to its revision and improvement.

The writer has been engaged in a study of Middle Devonian lithologic and faunal assemblage *types* and in the interpretive derivation of the environmental setting represented by each. The crinoidal limestone used as an illustration or test case throughout the present paper was chosen at random from a large body of Middle Devonian lithologic material; it represents the crinoidal phase, Croneis' Bed 9,[4] of the lower portion of the Grand Tower limestone exposed near Ozora, Ste. Genevieve County, Missouri. Twelve samples of this limestone were taken at 1-foot (time) intervals in a vertical section exposed on Quarry Hill and in the east bank of Little Saline Creek at the foot of Quarry Hill.

Acknowledgments.—The writer is indebted to Carey Croneis and Francis J. Pettijohn of the University of Chicago faculty in geology and paleontology. Under the tutelage of Dr. Croneis the dissertation and field studies which it necessitated were planned and carried out and the manuscript prepared. Dr. Pettijohn supervised and contributed liberally to the sedimentological phase of the problem. The laboratory and office work was done at and with the facilities of Walker Museum, University of Chicago. This paper represents the essential portion of a Ph.D. dissertation submitted to the faculty of the division of physical sciences, University of Chicago.

II. Sedimentary Petrography (Petrographic Analysis)

A. STUDY METHODS

The form of stratigraphic analysis which this paper propounds involves the use of the manifold study procedure graphically outlined in Figure 1. The procedure brings into play a series of checks and balances by which errors tend to be averaged out. The use and coördination of the various methods in the study of a sedimentary rock allow a convergence of evidence with regard to the attributes, properties, and structures. Any one method alone, such as thin-section examination, may not yield complete and reliable results, but when combined and coördinated with binocular microscopic examination of rock fragments and polished sections, with insoluble-residue studies, simple chemical tests, sieve and pipette analysis, and so forth, a degree of order and certainty emerges, and data are provided for the painting of a comprehensive picture of the sedimentary assemblage.

[4] C. Croneis, "The Devonian of Southeastern Missouri," *Illinois Geol. Survey*, Devonian Symposium Volume (in press).

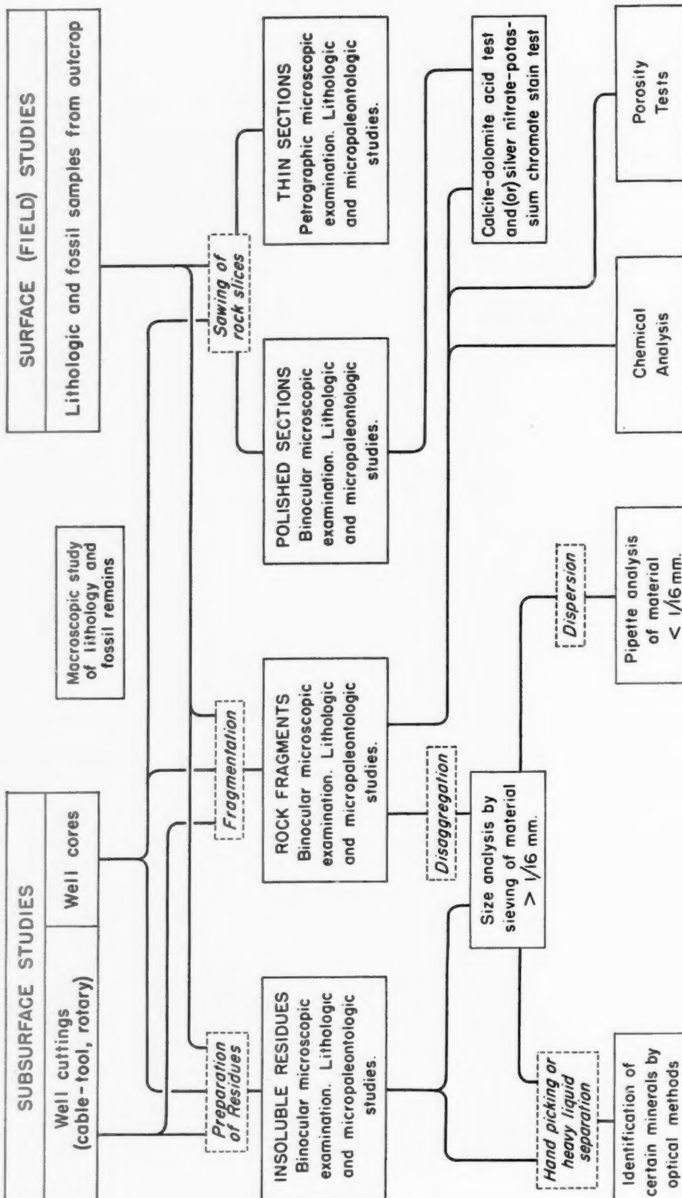


FIG. 1.—Flow outline of laboratory operations.

A handy outline for field study and description has been prepared by Goldman and Hewett.[5] Field observations should include study of the orientation and distribution of fossil remains and determination of the relative abundance of different morphologic types. Lithologic and fossil samples should be collected according to a plan and should be marked so as to show orientation with respect to bedding planes. Study of large-scale sedimentary structures must be carried out in the field, as must also the description of the attributes and properties of the coarse or rudaceous materials of cobble and boulder grades. The finer-grained sediments may be sampled and studied in the laboratory.

Insoluble residues employed by the writer have been prepared according to a procedure formulated by Workman.[6] This procedure includes separation of a residue into two fractions: (1) a sand fraction with grains greater than 1/16 mm. in diameter, and (2) a silt and clay fraction with grains less than 1/16 mm. in diameter. The separation is accomplished by a decantation procedure utilizing the differential settling velocities of the different sizes of components.

Chemical analyses of sediments are helpful in determining calcite-dolomite ratios, in determining the amount of organic (carbonaceous or bituminous) matter present, and in other qualitative and quantitative phases of compositional study. Chemical tests employed by the study procedure here propounded include the hydrochloric acid test and the silver nitrate-potassium chromate stain test[7] for differentiating calcite and dolomite. In the case of limestones composed of an aggregate of calcite and dolomite grains, the stain test permits determination of the calcite-dolomite ratio by a simple method of counting stained and unstained grains in a sample.

The degree of accuracy permitted by the methods and procedure here propounded obviously is not high, but it is adequate to meet the immediate needs of stratigraphic research. The data are in general accurate to within 5 per cent for the major constituents and to within 1 or 2 per cent for the minor components.

B. GENESIS OF SEDIMENTARY COMPONENTS

Genetic classification.—A rigorous genetic classification of sedimentary rock components must provide the answer to three questions. First, *where* was the component formed in relation to the site of final deposition? Was it formed in place or was it formed elsewhere, transported, and deposited? In other words, is the component autochthonous (Au) or allochthonous (Al)? Second, *when* was the component formed in relation to the time of deposition of the sediment? It is obvious that allochthonous components originate before accumulation of the

[5] M. I. Goldman and D. F. Hewett, "Schedule for Field Description of Sedimentary Rocks," *Natl. Research Council Comm. on Sedimentation Rept.* (Washington, D. C., 1928).

[6] L. E. Workman, Illinois State Geological Survey, typewritten copy of insoluble-residue procedure.

[7] W. C. Krumbein and F. J. Pettijohn, *Manual of Sedimentary Petrography*, p. 496. D. Appleton-Century Company, New York (1938).

deposit of which they are a part and are therefore ***progenetic.*** On the other hand, autochthonous components may originate either approximately contemporaneous with (*syngenetic*) or after (*epigenetic*) the genesis of the deposit. The third and final question pertains to *how* the component was formed, to the source of its material and to the process by which it originated.

The genetic classification of components which this paper introduces is here outlined. Examples are cited of deposits belonging for the most part in the various categories outlined.

I. ALLOCHTHONOUS COMPONENTS (those formed elsewhere and transported to site) (*Al*)
- A. *Progenetic* (*Pro*)
  - 1. Preëxisting rock source (weathering) (*pr*)
    - a. Katamorphic alteration products
      Ex: marine clay from igneous rock source
    - b. Differential solution products
      Ex: quartz sand from quartzose sandy limestone
    - c. Products of mechanical agencies
      Ex: transported arkose from granite terrane
  - 2. Transported chemical precipitate (*cp*)
    Ex: some lithographic limestones
  - 3. Volcanic source (pyroclastic) (*vol*)
    Ex: volcanic ash
  - 4. Transported material of organic origin (*org*)
    Ex: some crinoidal limestones, *Globigerina* ooze, *et cetera*

II. AUTOCHTHONOUS COMPONENTS (those formed in place and untransported) (*Au*)
- A. *Syngenetic* (*Syn*)
  - 1. Preëxisting rock source (weathering) (*pr*)
    - a. Katamorphic alteration products
      Ex: residual clay soil from granite
    - b. Differential solution products
      Ex: residual chert breccia from cherty limestone, tripoli from siliceous limestone
    - c. Products of mechanical agencies
      Ex: intraformational limestone breccia
  - 2. Primary chemical precipitate (*cp*)
    Ex: geyserite, calcareous tufa
  - 3. Primary chemical replacement (*re*)
    Ex: certain dolomites, phosphorite, *et cetera*
  - 4. Organic origin (*org*)
    Ex: coral and algal colonies of reef core
- B. *Epigenetic* (*Epi*)
  - 1. Preëxisting rock source (*pr*)
    - a. Katamorphic alteration products
      Ex: limonite altered from primary detrital magnetite
    - b. Anamorphic alteration products
      - (1) Recrystallization *without* mineral change
        Ex: marble from limestone
      - (2) Recrystallization *with* mineral change
        Ex: wollastonite from quartzose limestone
    - c. Differential solution products
      Ex: clay from phreatic solution of limestone
    - d. Products of mechanical agencies (diastrophic)
      Ex: fault breccias, cataclastic breccias, *et cetera*
  - 2. Secondary chemical precipitate from vadose or phreatic waters (meteoric or juvenile) (*cp*)
    - a. Introduced in voids (*cement*)
      Ex: calcite cement in quartz sandstone
    - b. Secondary growths
      Ex: quartz secondary enlargements in quartz sandstone
  - 3. Secondary chemical replacement (*re*)
    Ex: chert replacing limestone

Sedimentary components of cosmic origin are not considered in the foregoing genetic outline. Some of the red clay and associated small glass beads of deep-sea deposits are believed to be of this origin. This material and meteoritic fragments are, however, of little importance from the stratigraphic viewpoint.

Genetic analysis.—Some sediments are *end-member types* in that they are composed almost entirely of components from but a single genetic category. On the other hand, many sedimentary deposits derive their constituents from several categories and are therefore genetically complex.

The illustrative crinoidal sediment (Pl. I) is not genetically homogeneous inasmuch as it is a composite of several genetically distinct component types, as indicated by the analysis of Table I.

TABLE I

Genetic Analysis of Crinoidal Sediment

Genetic Class	*Sedimentary Material*	*Per Cent (Average of 12 Samples)*
Transported preëxisting rock material (*Al, Pro, pr*)	Quartz, tourmaline, rutile, magnetite	8–10
Transported material of organic origin (*Al, Pro, org*)	Crinoidal debris—columnals, *et cetera*	75–80
Transported preëxisting rock origin (?) or formed in place by chemical and (or) organic agencies (?)	Glauconite; finely divided and in aggregates	1 (approx.)
Autochthonous organic remains, untransported (*Au, Syn, org*)	Colonial corals, cup corals, brachiopods, pelecypods, *et cetera*	5–10
Epigenetic katamorphic alteration products (*Au, Epi, pr*)	Limonite from alteration of detrital magnetite	Less than 1
Secondary chemical precipitate (*Au, Epi, cp*)	Calcite cement in interstices	5–10

C. ATTRIBUTES OF SEDIMENTARY COMPONENTS

Sedimentary components have eight fundamental attributes which must be evaluated in petrographic analysis. These attributes pertain both to *individual* component grains and to components in the *aggregate*. For example, the attribute of *size* (mean diameter) of an individual quartz grain may be described in millimeters; this grain may be part of a quartz sand or sandstone, in which case the size distribution of associated grains in the sandstone aggregate also must be evaluated. Aggregate size determination must include an evaluation of *average size* and *sorting as to size* and may be presented statistically in terms of a frequency distribution or histogram; this also applies to the aggregate description of the other fundamental attributes.

1. COMPOSITION

Composition is an important attribute in that it determines certain properties both of the component grains and of the rock mass or aggregate. These include optical properties such as color, mechanical properties such as hardness and specific gravity, chemical properties such as solubility in water and reactivity with acid, and so forth.

Composition of sedimentary components may be designated in terms of mineral-species names or rock-type names (in case of rock fragments). Some sedimentary rocks are homogeneous or well sorted as to composition, an example being the Devonian Sylvanian sandstone of Michigan which in general consists of more than 99 per cent quartz grains. As indicated by Table II, the crinoidal sediment which this paper describes is rather homogeneous and shows good sorting as to composition, more than 96 per cent of the aggregate consisting of two mineral species, calcite and quartz.

The aggregate mineral composition of a sediment may be described by the use of mineral adjectives, such as quartzose, calcitic, dolomitic, argillaceous, and micaceous, which represent the dominant mineral species composing the aggregate. If the aggregate is composed largely of rock fragments, rock-type adjectives should be employed, such as *granitic* conglomerate, *basaltic* breccia, and *lithographic limestone* breccia.

TABLE II

COMPOSITION AND STRUCTURE OF COMPONENTS

Composition	*Structural Type of Components*	*Per Cent**
Quartz	Uni-grained mineral particles; crystalline structure	7-8
Tourmaline, rutile, magnetite	(same as foregoing)	Less than 1
Limonite	Multi-grained pellets; no definite internal structure	Less than 1
Glauconite	Multi-grained particles and aggregates; no definite internal structure	1 (approx.)
Bituminous (hydrocarbon) particles		Less than 1
Calcite	Uni-grained particles of organic (crinoidal) origin	75-80
Calcite	Multi-grained organic structural components; remains of brachiopods, corals, *et cetera*	5-10
Calcite	Finely crystalline interstitial cement	5-10

* Average of 12 samples collected at 1-foot vertical (time) intervals in section exposed at Quarry Hill and in east bank of Little Saline Creek.

2. INTERNAL STRUCTURE

A sedimentary component, whether uni-grained or multi-grained, is an individual entity which reacts as a unit during transportation or is formed in place

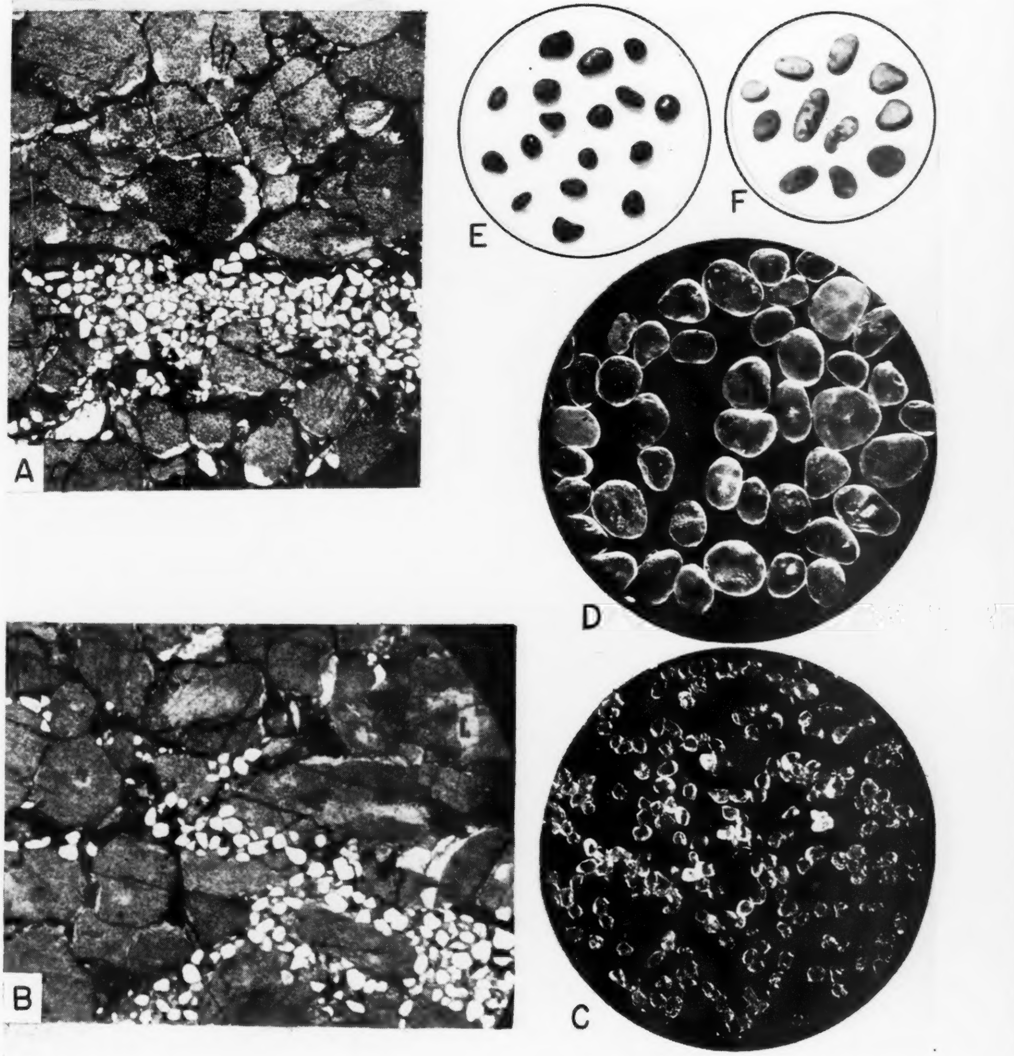


Plate I

Photomicrographs of thin sections and insoluble-residue material. Grand Tower limestone, crinoidal phase (Bed 9), Quarry Hill, Ozora, Missouri.

A, B—Thin-section views (×16). Crinoidal débris (gray), smaller size quartz grains (white), calcite cement (black).

C, D—Views of insoluble-residue quartz sand (both ×16) showing two distinct size distributions represented.

E—Grains of detrital magnetite and limonite altered from detrital magnetite (×25).

F—Grains of pale brown, detrital tourmaline (×40, transmitted light).

as an entity either during or after genesis of the sediment of which it is a part. The *internal structure* of a component is one of the eight fundamental attributes; the various types of structures are listed and illustrated in the outline classification which follows. The internal structure of the component grains of the illustrative crinoidal sediment is described in the middle column of Table II.

I. Uni-grained Mineral Particles
  A. Crystalline structure
    Ex: quartz grains in sandstone; calcite grains in limestone
  B. Amorphous structure
    Ex: grains of limonite
II. Multi-grained Components of Mechanical Origin
  A. Rock fragments (derived from preëxisting rock)
    Ex: granite cobbles, schist pebbles, limestone granules
  B. Clay galls
  C. Mud balls
III. Multi-grained Components of Volcanic (Magmatic) Origin
  Ex: bombs, lapilli, *et cetera*
IV. Multi-grained Components of Organic Origin
  A. Individual structures or fragments thereof
    Ex: shells and tests of invertebrates; bones of vertebrates
  B. Colonial structures or fragments thereof
    Ex: colonial coral structures, algal structures, *et cetera*
V. Multi-grained Components of Concretionary Origin
  A. Concretionary bodies with *concentric structure*
    1. Oölites (calcite, *et cetera*)
    2. Pisolites (bauxite, *et cetera*)
    3. Concentric concretions
  B. Concretionary bodies with *radiate structure*
    1. Spherulites (pyrite, calcite, *et cetera*)
    2. Radiate concretions
  C. Concretionary bodies with no definite internal structure
    1. Pellets
      Ex: glauconite pellets, siderite pellets, faecal pellets, *et cetera*
    2. Nodules
      Ex: phosphatic nodules, chert nodules
    3. Structureless concretions
      Ex: limestone concretions

The internal structure of sedimentary components is a textural attribute; its mass or aggregate aspect, in the texture of a sediment, may be described by the use of such structural adjectives as oölitic, pisolitic, concretionary, spherulitic, nodular, uni-grained fragmental, and multi-grained fragmental (composed of rock fragments). If the sediment contains a significant portion of multi-grained components of organic origin, the mass textural aspect may be described by the use of such adjectives as foraminiferal, coralliferous, and pelecypodan.

3. SIZE

Size is a textural attribute and is one of the most important of the eight fundamental attributes. If sedimentary particles were perfect spheres, a definition of size would be simple; natural particles, however, are highly variable in shape, and evaluation of grain size must therefore consider grain shape. Grain size may be expressed in terms of mean diameter, which is the arithmetic average of the three principal diameters, length, breadth, and thickness.

Size analysis.—Size analysis of a sedimentary aggregate may be accomplished by the use of one or more of the methods here listed and described. The goal is subdivision of a sample into size classes or grades and calculation of the relative proportion in each class. Several grade scales of size have been proposed; Wentworth's modification of Udden's scale[8] is the one most widely used in this country.

TABLE III

SIZE CLASSIFICATION OF FRAGMENTAL AND CRYSTALLINE-TEXTURED SEDIMENTS

Mean Size Range (in Mm., Wentworth's Scale)	*Wentworth Grade Name*	*Fragmental-Textured Sediments; Aggregate Size-Roundness Designation*		*Crystalline-Textured Sediments; Aggregate Size Designation*	
Greater than 256	Boulder (*bl*)	Rudites	Boulder gravel, rubble (boulder conglomerate, breccia)	Phanerocrystalline	
256–64	Cobble (*cb*)		Cobble gravel, rubble (cobble conglomerate, breccia)		
64– 4	Pebble (*pb*)		Pebble gravel, rubble (pebble conglomerate, breccia)		
4– 2	Granule (*gn*)		Granule gravel, rubble (granule conglomerate, breccia)		Granular crystalline (*gnc*)
2– 1	Very coarse sand (*vcs*)	Arenites	Very coarse sand, grit (very coarse sandstone, gritstone)		Very coarsely crystalline (*vcc*)
1–1/2	Coarse sand (*cs*)		Coarse sand, grit (coarse sandstone, gritstone)		Coarsely crystalline (*cc*)
1/2 –1/4	Medium sand (*ms*)		Medium sand, grit (medium sandstone, gritstone)		Medium crystalline (*mc*)
1/4 –1/8	Fine sand (*fs*)		Fine sand, grit (fine sandstone, gritstone)		Finely crystalline (*fc*)
1/8 –1/16	Very fine sand (*vfs*)		Very fine sand, grit (very fine sandstone, gritstone)		Very finely crystalline (*vfc*)
1/16–1/256	Silt (*sl*)	Lutites	Silt (siltstone)	Micro-crystalline	Sublithographic (*sli*)
1/256–1 micron	Clay (*cl*)		Clay (claystone)		Lithographic (*li*)
Less than 1 micron	Colloidal particles		Colloidal aggregates		Cryptocrystalline aggregates

Grade scales and their use are described on pages 76–90 of the *Manual of Sedimentary Petrography* by Krumbein and Pettijohn. Wentworth's grade scale and its application to fragmental and crystalline-textured sediments are outlined in Table III. The more important methods of size analysis are as follows.

1. Sieve analysis of disaggregated rock sample or of insoluble residue. Components greater than 1/16 mm. in diameter thus separated into Wentworth grade sizes; sieve separates weighed and recorded.

[8] C. K. Wentworth, "A Scale of Grade and Class Terms for Clastic Sediments," *Jour. Geol.*, Vol. 30 (1922), pp. 377–92.

This method is applicable to insoluble residues only when the residue of sand size or larger constitutes at least 2 grams of the initial 50-gram sample. For residues smaller than this, visual measurement and estimation by a counting and tallying method are satisfactory.

2. Pipette analysis[9] of disaggregated rock sample or of insoluble residue. The form of stratigraphic analysis here propounded merely calls for separation and determination of the relative proportions of the clay and silt fractions. Sieved material less than 1/16 mm. in diameter is dispersed, and a water suspension of about 2% concentration is prepared in a liter cylinder graduate; the suspension is agitated, set at rest, and 2 hours and 3 minutes thereafter is sampled 10 cm. below the surface with a 20 cc. pipette; pipette sample is then dried and weighed and the weight multiplied by a factor (50) which converts it into terms of the total liter sample, i.e., *weight of clay fraction*. This weight is then subtracted from the weight of the total initial sample, and the remainder represents *weight of silt fraction*.
3. Visual measurement of disaggregated material. If dry grains are sprinkled on a slide, they tend to assume positions such that the shortest diameter (thickness) is approximately vertical. Thus the plane of the longest and intermediate diameters tends to be at right angles to the microscope tube; these diameters can be measured with the use of a binocular microscope fitted with a micrometer ocular. Sedimentary components larger than sand size may be measured with a ruler or caliper. The relative proportion of the sample in each of the size classes may be calculated by simple counting and tallying methods.
4. Visual measurement of grains in thin section or polished section or on surface of rock fragment. Grain diameters measured with the use of a micrometer ocular; observed radii corrected in accordance with theory of thin-section size analysis,[10] i.e., multiplied by 1.27. Relative proportion of the section sample in each of the size classes estimated by counting and tallying methods.

Presentation of size data.—A size analysis in the form of a histogram, such as that of Figure 2, should be accompanied by an evaluation of the *average* size and the degree of *sorting* as to size. Average size may be expressed in terms of the arithmetic mean of the diameter distribution, a measure which may be computed[11] readily from the size-frequency distribution or histogram. Sorting may be defined as the degree of concentration of data about an average, a high degree of concentration implying good sorting as to size. There are several statistical measures of sorting, but all are too time-consuming for widespread use in stratigraphical analysis. Sorting is evaluated by the writer as follows.

1. *Good sorting,* if 90 per cent of the sediment is concentrated in 1 or 2 size classes
2. *Fair sorting,* if 90 per cent is distributed through 3 or 4 size classes
3. *Poor sorting,* if 90 per cent is distributed through 5 or more classes

The mass textural aspect of grain size of a sedimentary aggregate may be described by the use of size adjectives, following the classification of Table III. In the case of fragmental-textured aggregates such adjectives should be employed as very coarse sandy, medium sandy, fine sandy, and silty; whereas for crystalline-textured aggregates such equivalent adjectives as very coarsely crystalline, medium crystalline, finely crystalline, and sublithographic may be employed. Where two or more size classes predominate in the aggregate, size may be described in a manner illustrated by the following examples: fine to coarse sandy, sublithographic to finely crystalline, silty medium sand, and coarse sandy pebble gravel.

Size analysis of crinoidal sediment.—The crinoidal phase of the Grand Tower limestone (Pl. I) described in the present paper, although now of crystalline

[9] W. C. Krumbein, "The Mechanical Analysis of Fine-Grained Sediments," *Jour. Sed. Petrology,* Vol. 2 (1932), pp. 140–49.

[10] Krumbein and Pettijohn, *op. cit.,* pp. 129–32.

[11] Krumbein and Pettijohn, *op. cit.,* p. 240.

texture, was deposited in the Devonian sea as a fragmental sediment, a quartzose crinoidal sand, the size distribution of which is portrayed graphically by Figure 2. The total volume of the crinoidal rock in the sampled section is divisible as follows.

	Per Cent, Volume
Transported fragmental material (shown in histogram, Fig. 2)	80–90
Untransported coral, brachiopod, pelecypod, *et cetera* remains	5–10
Finely crystalline calcite cement	5–10
Total	100

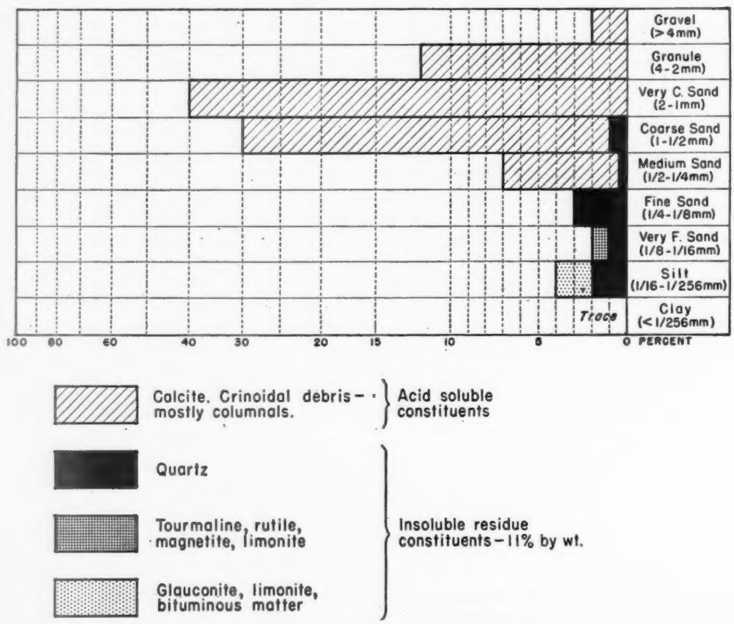


FIG. 2.—Size histogram of transported fragmental components, crinoidal phase of Grand Tower limestone. Average of 12 sets of samples collected at 1-foot vertical (time) intervals from section exposed on Quarry Hill and on east bank of Little Saline Creek.

The size distribution of the crinoidal débris was measured by thin section and polished section methods and by simple measurement of the columnals and other plates standing out in sharp weathered relief on rock surfaces. The grain size of the quartz and other acid-insoluble minerals was measured by sieve analysis of the insoluble rèsidue, which constituted 11 per cent of the rock by weight. The arithmetic mean diameter, as calculated from the size-frequency distribution, is 1.24 mm. This crinoidal sediment shows only a *fair* degree of sorting as to size, 90 per cent of the grains being spread through four size classes (granule through medium sand). The modal class, that showing maximum frequency, is

the very coarse sand class (2–1 mm.). At the time of deposition the crinoidal sediment would have been classified as a very coarse to coarse sand (Table III); after deposition and burial it assumed a crystalline texture as a result of cementation and recrystallization, and thus may now be classified as a very coarsely to coarsely crystalline limestone.

4. SHAPE

Grain shape, like size, is a textural attribute. Zingg's shape classification diagram[12] has been modified by the writer so as to include nine shape classes (Fig. 3), to which grains of sand size or larger may be referred.

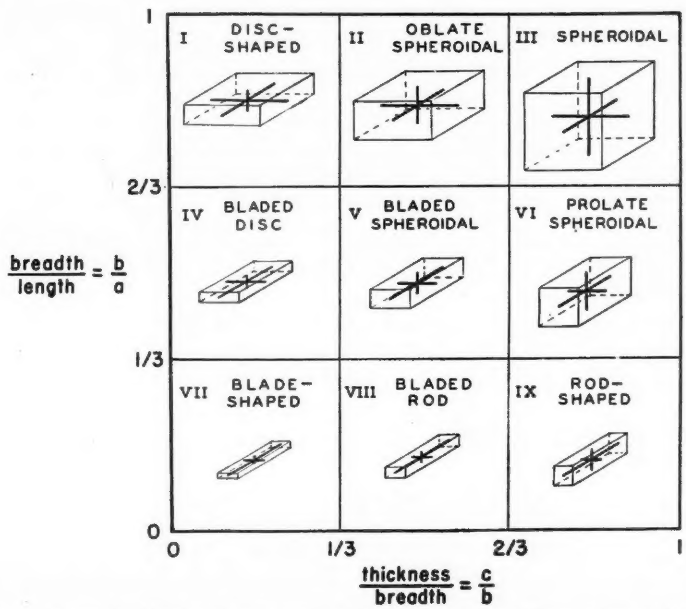


FIG. 3.—Shape-classification diagram modified from original plan of Zingg. *a*, length; *b*, breadth; and *c*, thickness. Boxes (parallelograms) which enclose the three diameters should be ignored; they are included so that shapes represented by diameters will be more apparent.

Shape analysis.—Shapes designated by Zingg's diameter-proportion scheme are determined by estimating the ratios between the three principal diameters (*a*, *b*, *c*). In the case of pebble, cobble, and boulder components, the diameters may be measured with a ruler or caliper; diameters of sand- and granule-size grains may be measured by means of a micrometer ocular and fine-adjustment screw. The long (*a*) and intermediate (*b*) diameters, approximately at right angles to the microscope tube, may be measured with the micrometer ocular. The thick-

[12] Th. Zingg, "Beitrag zur Schotteranalyse," *Schweiz. Min. u. Pet. Mitt.*, Bd. 15 (1935), pp. 39–140.

ness or short diameter (*c*) may be measured with a petrographic microscope by means of the fine-adjustment screw; the instrument is first focussed on the surface on which the grain rests and then on the upper surface of the grain itself, the difference of the micrometer readings representing the measure of thickness.

Zingg's diameter-proportion method of shape classification fails to provide a complete picture of the outline geometry of a grain. In some cases it may be desirable to supplement the shape-class designation with a term describing the geometric form of the grain. For example, in the plane of the *a* and *b* axes or diameters disc-shaped components (class I) may tend to be circular, pentagonal, triangular, square, and so forth. Wentworth[13] has assembled a series of well known geometric form designations which may be used to describe grain outlines. In the same paper he also lists three-dimensional shape terms, such as pyramidal, prismoidal, and wedge-shaped, which may be used in certain cases to describe the shape of grains as solid or three-dimensional bodies.

A shape analysis of a sediment may be presented in the form of a scatter diagram of points plotted on a diameter-ratio grid such as that of Figure 3, each point representing an individual component of the aggregate. In addition, shape analysis should evaluate the *average* shape and the degree of *sorting* as to shape. The shape class or classes having the maximum concentration of points may be designated as the average. If the grains of a given sediment tend to be grouped along a boundary between two classes, the average shape may be expressed by combining the two class numerals. Sorting as to shape may be evaluated in the same manner as sorting as to size. If 90 per cent of the grains is concentrated in 1 or 2 shape classes, the sedimentary aggregate shows *good* sorting; if 90 per cent is distributed through 2 or 3 shape classes, *fair* sorting is indicated; if 90 per cent is distributed through 4 or more shape classes, a condition of *poor* shape sorting obtains.

Shape analysis of crinoidal sediment.—The average shape of the coarse to medium quartz sand (Pl. I, D) in the illustrative crinoidal sediment is approximately along the boundary between the spheroidal and the prolate spheroidal classes (III–VI); the shapes of these grains, however, range into the bladed spheroidal (V) and oblate spheroidal (III) classes. The average shape of the crinoid columnals and other plates (Pl. I, A, B) is somewhere near the juncture of classes I, II, and IV, disc-shaped columnals being dominant. The tourmaline grains (Pl. I, F) are dominantly prolate spheroidal (VI), and the limonite and magnetite grains are for the most part bladed spheroidal (V). The crinoidal sediment thus shows fair to poor sorting as to shape, 90 per cent of the grains being spread through 4 or 5 shape classes; this condition is due to the fact that the grains are of heterogeneous derivation, some representing little transported organic débris and others derived from preëxisting rocks and having undergone several cycles of transport.

[13] C. K. Wentworth, "An Analysis of the Shapes of Glacial Cobbles," *Jour. Sed. Petrology*, Vol. 6 (1936), pp. 85–96.

5. ROUNDNESS

The attribute of grain roundness pertains to the degree of regularity of the surface or outline and to the degree of sharpness (radius of curvature) of edges and corners. Roundness is distinct from shape inasmuch as two grains of the same diameter ratio or shape may show different degrees of roundness.

Roundness analysis.—Several mathematical measures of roundness have been proposed, but none is suitable for use in the rapid study procedure here propounded. In this procedure roundness analysis must be accomplished by simple visual comparison with a set of standards depicting various roundness classes.

A familiar roundness classification method involves placing the components in one or more of four classes, the limits of which are arbitrary; the classes are as follows.

1. *Angular* (*A*)—irregular grain surface dominated by edges and corners all of which are sharp; grain either represents an unworn crystal or a fractured particle
2. *Subangular* (*SA*)—edges and corners still prominent on grain surface but tend to be less sharp and slightly curved or rounded (larger radius of curvature)
3. *Subround* (*SR*)—edges and corners mostly curved; grain outline still somewhat irregular
4. *Round* (*R*)—edges and corners absent; surface outline of grain a smooth curve tending toward an oval or circular shape.

Classification may be accomplished by visual comparison of the grains with the set of illustrations of Figure 2 of the paper by Russell and Taylor[14] on Mississippi River sands.

The other visual roundness classification method involves placing the components of a given sediment in one or more of the nine roundness classes illustrated by Figure 4. This image diagram was presented in a paper by Krumbein,[15] the roundness of the pebbles selected to illustrate each of the nine classes (0.1–0.9) was measured from grain projections utilizing Wadell's formula for roundness of plane figures. Although this image diagram was prepared to make possible visual estimation of pebble roundness, it also is applicable to components in the granule and sand grades of Wentworth's size scale. Roundness classes 0.1–0.2 are roughly equivalent to the *angular* class of the other classification system; 0.3–0.4 to the *subangular* class; 0.5–0.7 to the *subround;* and 0.8–0.9 to the *round.*

A problem is presented by grains the outlines of which show composite roundness, such as those at the lower right of Figure 4. Such grains combine two or more roundness classes and may constitute a significant portion of a sedimentary deposit. They are formed by fracture of grains which previously had undergone rounding. In classifying them it is best to employ a dual number designation, the first denoting the roundness of the major portion of the grain outline and the second the minor portion. For example, the grain marked .3 in the diagram would be classified as .7//.1. This provides a clearer picture of the actual composite roundness condition than does the misleading single number.

[14] R. D. Russell and R. E. Taylor, "Roundness and Shape of Mississippi River Sands," *Jour. Geol.*, Vol. 45 (1937), pp. 225–67.

[15] W. C. Krumbein, "Measurement and Geological Significance of Shape and Roundness of Sedimentary Particles," *Jour. Sed. Petrology*, Vol. 11 (1941), Pl. 1, p. 68.

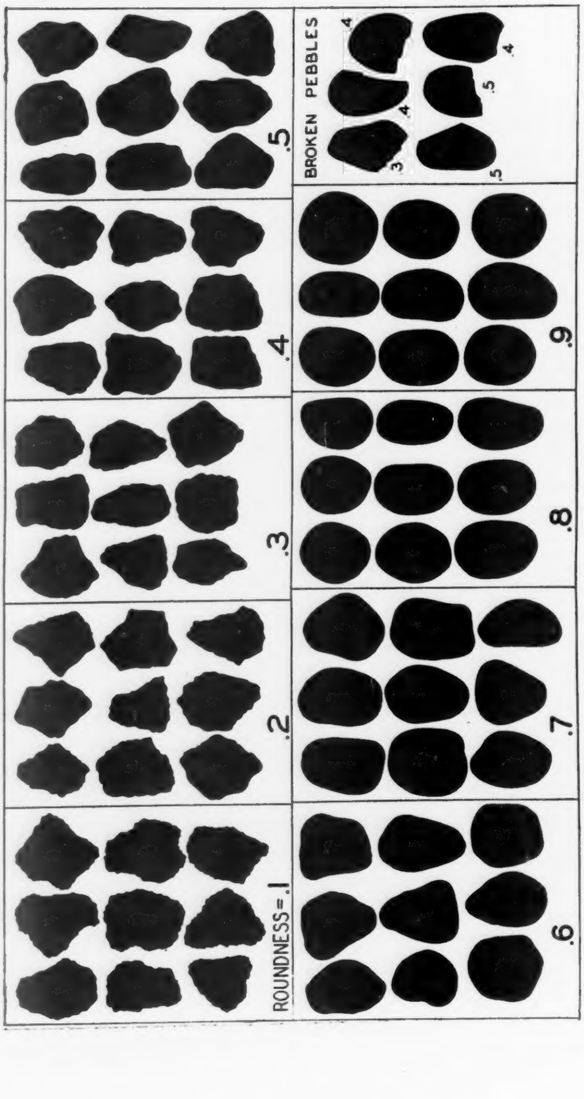


FIG. 4.—Images for visual comparison in classifying grains according to roundness. Diagram prepared by Krumbein for estimating pebble roundness; also applicable to granule and sand sizes.

A roundness analysis, utilizing the classification scheme of Figure 4, may be presented in the form of a histogram or in the form of a diagram such as that of Figure 5. The relative proportion of the total sediment in each of the roundness classes may be estimated by a simple counting and tallying method. The analysis should include a statement as to the average roundness and the degree of sorting, the latter being expressed as good, fair, or poor, following the procedure used in the case of size sorting.

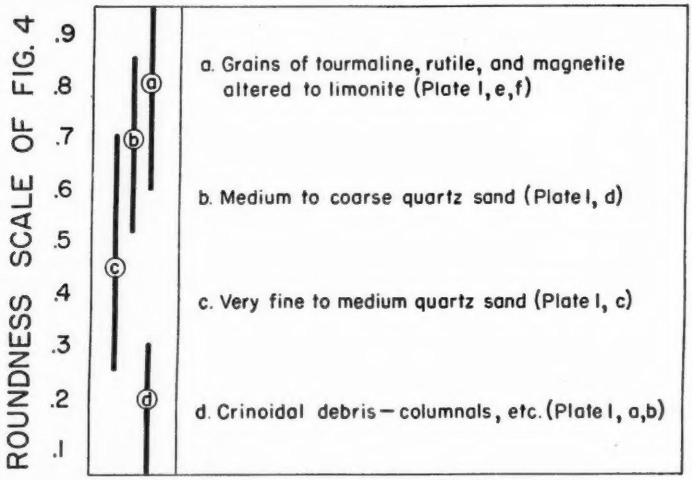


FIG. 5.—Roundness analysis of transported fragmental components of crinoidal phase (Bed 9), Grand Tower limestone.

Roundness of sedimentary components is a textural attribute, and its mass or aggregate aspect, in the texture of a given sediment, may be indicated by the use of such terms as gravel *versus* rubble, conglomerate *versus* breccia, and sandstone *versus* gritstone. Aggregate roundness also may be designated by the use of adjectives such as angular-grained, subangular-grained, subround-grained, and round-grained.

The analysis of Figure 5 shows the crinoidal sediment (Pl. I) to be poorly sorted as to roundness, a feature which is due to the fact that the grains are of heterogeneous derivation. As would be expected, the little transported crinoidal débris is for the most part angular, whereas the quartz and heavy mineral grains, having undergone several cycles of transport, are subround to round. The position of the encircled letters (*a–d*) indicates the average roundness for the different component types, and the extent of the lines suggests the range of variation.

6. SURFACE TEXTURE

The attribute of surface texture, unlike roundness, refers to the finer details of grain surfaces, those features that do not affect the surface outlines of the particles. The surface texture classification here employed is patterned after that of Williams.[16] As indicated by the following outline, the surface of a sedimentary particle has two fundamental textural aspects: degree of surface *relief* and degree of *luster*.

- I. Surface Relief of Particle
  - A. Smooth (*sm*)
  - B. Rough
    1. Frosted (ground-glass surface) (*fr*)
    2. Etched (result of solvent action) (*et*)
    3. Faceted (result of secondary growths) (*fa*)
    4. Striated, scratched or furrowed (*st*)
    5. Percussion or chatter marked (*pm*) (*cm*)
    6. Pitted (*pi*)
    7. Ridged (*ri*)
- II Surface Luster of Particle
  - A. Dull (*D*)
  - B. Polished (glossy) (*P*)

A grain surface may be smooth or rough independent of the luster; it may likewise be dull or polished independent of the relief. Classification of components according to surface texture must therefore be binary, in that it must evaluate both the surface relief and degree of luster; for example, quartz grains may be smooth and polished (*sm, P*), and frosted and dull (*fr, D*). In some cases different types of relief may be coëxistent on the same grain; that is, the grain may be both striated and pitted or both etched and smooth, and so forth. Furthermore, certain component types within the aggregate may show variation in surface texture.

Inasmuch as geologic agents leave their impress on the surfaces of grains, surface textures are significant in genetic studies. Some textures can be formed in quite different ways; for example, a frosted surface may be formed by rigorous wind (sand-blast) action, by chemical etching, or by incipient secondary enlargement. Surface textures may be inherited, formed during transportation, or formed intrastratally by post-depositional agents.

Surface texture analysis of crinoidal sediment.—The coarse to medium quartz sand grains (Pl. I, D) show a somewhat polished luster and vary in relief from smooth to etched and frosted; their surface texture might be expressed in abbreviated form as follows: *P, sm* to *et* and *fr*. The medium to very fine quartz sand grains (Pl. I, C) are *P, sm* to *et*. The tourmaline, rutile, magnetite, and limonite grains are *P, sm*. The original surface texture of the crinoidal particles has been greatly altered as a result of post-depositional recrystallization, solution, and cementation. The columnals and other plates stand out in sharp relief on weathered rock surfaces and are dull in luster and have a rough surface relief marked by etched, striated, and pitted irregularities.

[16] L. Williams, "Classification and Selected Bibliography of the Surface Textures of Sedimentary Fragments," *Nat. Research Council Comm. on Sedimentation Rept.* (1937), pp. 114–28.

7. RELATIVE POSITION OF COMPONENTS IN SPACE

The position in space of an individual component, although constituting a fundamental sedimentary attribute, is of little significance when considered from the viewpoint of an individual grain standing alone. When considered from the aggregate point of view, however, and applied to the mutual space arrangement of individuals in the aggregate, this attribute is of descriptive importance. It is of greatest importance in the case of deposits, such as the crinoidal sediment described in this paper, the components of which show differentiation as to mineral composition, and (or) size, and (or) shape, and so forth. The space distribution of minor component types, those constituting less than half of the aggregate, may be described in a manner exemplified by the following phrases: in *irregular patches* or *stringers* in the aggregate, in the form of *tabular bodies* (vertical to horizontal bands), *evenly disseminated* throughout the aggregate, and distributed *at random* within the aggregate.

The space arrangement attribute also is significant in the case of sediments composed mostly of one component type, such as a pure quartz sand which shows only little differentiation in composition, size, or shape. Space arrangement under such homogeneous conditions has been studied experimentally by means of aggregates of artificial spheres. When the spheres are arranged in a cubic grid pattern, so that lines connecting their centers are at right angles to each other, the lowest degree of packing and the highest porosity result. When arranged in rhombohedral or other grid patterns, in which lines connecting sphere centers diverge from the right-angle condition, higher packing and lower porosity result because of decrease in the volume of intergrain voids.

Thus far, this attribute of mutual space arrangement has not been studied in detail, is not amenable to simple classification and must therefore be described verbally in each case. It, together with the attributes of size, shape, and fabric, controls the property of packing.

Space arrangement of components in crinoidal sediment.—In the crinoidal limestone, pictured in thin section in Pl. I, A, B, the crinoidal débris constitutes the major component type, and the other component types show an interesting space distribution within the aggregate. The medium to coarse quartz sand occurs as isolated grains distributed at random like the crinoid columnals which they approach in size. In contrast, the silt and fine sand, composed of quartz, tourmaline, rutile, limonite, magnetite, and glauconite, occur throughout the coarser aggregate in the form of irregular patches, stringers, and bands.

This attribute of relative space distribution of components reveals much with regard to the environment and mode of transportation and deposition and is therefore deserving of study. The coarse quartz sand previously mentioned was deposited probably from traction transport in the same manner as the crinoidal particles; thus, the space distribution of these two component types is similar. As described in subsequent pages, the silt and fine sand probably were deposited from suspension transport, during times of quiet water, in the form of thin

layers, some of the grains percolating down through the interstices of the larger crinoidal grains.

8. ORIENTATION OR FABRIC

The attribute of *orientation* applies to an *individual* component and is expressed as the angle of dip and strike of the maximum projection plane, this representing the plane defined by the long and intermediate diameters (length and breadth) of the component. The term *fabric* denotes orientation in the aggregate; that is, the fabric of a sedimentary deposit represents a *composite* of the orientations of certain or all of the individual components. Measurement of orientation or fabric is possible only in the case of sediments of sand size or larger (sand through boulder sizes). This attribute obviously is related to grain shape and pertains only to sediments whose grains are not equidimensional; spherical grains have no orientation. *Primary fabric* refers to the orientation of the components that is instituted during deposition; this may be changed during or after burial and compaction.

An interesting example of sedimentary fabric is provided by the basal conglomeratic phase of the Devonian St. Laurent limestone formation at Quarry Hill, near Ozora, Missouri. The pebbles of this conglomerate consist of three preëxisting rock types: (1) sandstone fragments, probably derived from the underlying Beauvais sandstone, (2) sublithographic limestone, possibly eroded from the upper phase of the Grand Tower limestone, and (3) chert pebbles, the character of which suggests derivation from the earlier Devonian Bailey chert. These pebbles are for the most part in mutual contact and are set in a matrix of quartz sand cemented with calcite; they vary in shape through the shape classes II, III, V, and VI (Fig. 3). Large sawed sections of the conglomerate indicate that the pebbles have a preferred orientation throughout the aggregate; that is, their long diameters tend to be similarly oriented in random cross sections and thus show a parallel type of fabric.

The fabric of the afore-described conglomerate is significant in environmental interpretations. The sediment probably was deposited as a beach gravel in which the most common shape class was the prolate spheroidal (VI). The orientation of beach pebbles has been studied by Fraser,[17] who found by statistical studies that roller-shaped pebbles commonly lie with their long diameters parallel with each other and with the shoreline. Fraser attributes this parallel fabric to the tendency for waves to swing pebbles into such a position or to the tendency for the pebbles to roll with their long diameters perpendicular to the direction of current movement.

Fabric classification and analysis.—Description and classification of a sedimentary deposit according to its fabric is a difficult problem, an understanding

[17] H. J. Fraser, "Experimental Study of the Porosity and Permeability of Clastic Sediments," *Jour. Geol.*, Vol. 32 (1935), pp. 910–1010.

of which may be gained from a paper by Krumbein.[18] The classification scheme proposed by the present writer is as follows.

A. Random orientation (non-parallelism) of individual components with respect to both their maximum projection planes and their long diameters
B. Preferred orientation (parallelism) of maximum projection planes of components (long diameters in random orientation)
C. Preferred orientation (parallelism) of long diameters of components (maximum projection planes in random orientation)
D. Preferred orientation (parallelism) of both maximum projection planes and long diameters of components.

Classification of a sedimentary aggregate which shows a preferred orientation (classes B, C, D) calls for two further descriptive considerations: (1) the *angle of inclination* (dip) of the maximum projection planes and (or) long diameters with respect to horizontal or with respect to the bedding planes, and (2) the *compass direction* (strike) of the maximum projection planes. The orientation of components of a deposit may be expected to vary, and this variation, as in the case of the other attributes, calls for evaluation of the *average* angle of dip and direction of strike and the degree of *sorting*. Detailed fabric analyses are beyond the scope of the present paper; methods of analysis and presentation, including orientation histograms and polar coördinate diagrams of dip and strike, are described in the afore-cited paper by Krumbein.

Imbrication is a type of fabric, formed under certain conditions in stream beds and along beaches, which is characterized by a preferred orientation (parallelism) of the maximum projection planes of the components at an angle to the bedding planes. Imbrication is not a sedimentary structure, as is commonly supposed, inasmuch as it involves grain-to-grain relationships rather than mass relationships of grain aggregates. Another type of fabric phenomenon in sedimentary rocks is represented by the parallel orientation of clay flakes in certain clay shales, especially those composed of illite minerals; this fabric renders such rocks cleavable in planes ordinarily parallel with the bedding planes.

Fabric of crinoidal sediment.—The illustrative crinoidal sediment (Pl. I) shows a random orientation of individual components with respect to both their maximum projection planes and their long diameters. Thus the fabric of this rock belongs in category *A* of the classification scheme.

D. PROPERTIES OF SEDIMENTARY AGGREGATES

Sediments and sedimentary rocks have certain mass features, here termed *properties* which call for description in petrographic analysis. Just as the mass characteristics of a society are determined by the attributes of its individuals, so also are the mass properties of a sedimentary aggregate governed by the basic attributes of the particles of which it is made. In other words sedimentary properties and their values are functions of the parameters of the attributes.

[18] W. C. Krumbein, "Preferred Orientation of Pebbles in Sedimentary Deposits," *Jour. Geol.*, Vol. 47 (1939), pp. 673–706.

Eight properties of stratigraphic significance are described here in summary fashion. Such properties as plasticity, hygroscopicity, fusibility, and specific gravity are not particularly important from the stratigraphic point of view and therefore are not included in the list.

COLOR

The property of color of a sedimentary aggregate is conditioned by four factors: (1) the summary or total effect of the colors of the component mineral grains and (or) rock fragments, (2) the color of the interstitial cement or matrix material, if present, (3) the presence of mineral pigment either coating the grains or disseminated throughout the cement or matrix, and (4) the degree of fineness of the grains. The last factor (4) is important in the case of very fine-grained sediments; the smaller the average particle size the darker the color of the aggregate. Pigmentary materials which may determine rock coloration include bituminous and carbonaceous material, oxides of iron, finely divided glauconite, ferrous sulphide, and so forth. Accurate color determination is a most difficult problem because of subjective errors and the lack of a generally accepted standard scale of colors.

Color of crinoidal sediment.—The crinoidal limestone of this report is light buff gray in color and has a slight greenish cast, locally, where glauconite is relatively more abundant. The predominant light gray color is imparted by the calcite grains of crinoidal origin, by the quartz grains, and by the calcite cement, pigmentary material being absent. The superimposed buff coloration of slight intensity is caused by the presence of limonite particles (Pl. I, Table II).

MASS CHEMICAL COMPOSITION (CHEMICAL ANALYSIS)

The property of mass chemical composition, evaluated in the form of a partial or complete chemical analysis of a sediment, is an important aspect of petrographic study and must be considered if the complete story is to be told for a deposit. This property may be summarily evaluated for a given sediment by the use of one or more adjectives which describe the dominant chemical composition; for example, siliceous, calcareous, magnesian, ferruginous, carbonaceous, and phosphatic.

A chemical analysis is a valuable tool in the study of fine-grained sediments, the mineralogy of which often defies determination by ordinary methods. From chemical analyses the quantitative mineral composition of a sediment often may be determined by recasting the chemical constituents in terms of the mineral species known to be present. This method of study also provides information about the MgO content and the calcite-dolomite ratios of limestones. In the case of sediments used for commercial purposes study of the property of mass chemical composition permits quantitative determination of the presence of deleterious and desired constituents. The organic content of sediments, important in the study of source beds of petroleum, likewise may be evaluated from chemical

analysis; determination of organic content and its significance have been described by Trask.[19]

Chemical composition of crinoidal sediment.—Following is a partial chemical analysis of a composite sample of the crinoidal limestone of this report, samples from several horizons in Bed 9 having been mixed.

SiO_2	10.04
Fe_2O_3	0.66
Al_2O_3	0.49
CaO	49.20
MgO	0.36
Ignition loss (mostly CO_2)	38.17
Alkalies	Trace
	98.92

The analysis was made in the chemical laboratory of the Kansas State Geological Survey. Any H_2O present is included under ignition loss; some FeO may be contained in the Fe_2O_3 category.

Most of the silica is in the form of the mineral quartz; a minor amount is combined in the minerals glauconite and tourmaline (see Table II). Most of the Fe_2O_3 is in the form of limonite and magnetite although some must be contained in the other minerals. The CaO is dominantly combined with CO_2 as calcite.

ACID SOLUBILITY (CHARACTER OF RESIDUE)

The chemical property of a sediment of being soluble or insoluble in acid (HCl) finds concrete stratigraphic expression in the form of insoluble residue studies of limestones and dolomites. The character of an insoluble residue and its per cent by weight of the total sediment constitute an important sedimentary property useful in correlation and other phases of stratigraphic research. Procedures for preparation of residues have been developed by many workers; that employed by the writer was formulated by Workman and has been described in the section on study methods.

Results of insoluble-residue studies may be plotted graphically utilizing a bar diagram, such as that employed by Ireland,[20] the width of each bar representing the thickness of the sedimentary section sampled and the length of each bar representing the residue's per cent by weight of the total sample. The length of each bar may be subdivided into sections designated by different symbols, which represent the different types of material composing the residue. These bars may be plotted on well strips or on strips representing sections sampled in the field, and correlation between strips may be accomplished by matching the percentages by weight of the residues and by matching the character of the material, compositional and textural.

[19] P. D. Trask, *Origin and Environments of Source Sediments of Petroleum*, pp. 18–66, 110–205. Gulf Publishing Company, Houston, Texas (1932).

[20] H. A. Ireland, "Use of Insoluble Residues for Correlation in Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 20, No. 10 (October, 1936), pp. 1086–1121.

The insoluble-residue content of the crinoidal limestone of this report constitutes 11 per cent by weight of the aggregate and is illustrated graphically in the histogram of Figure 2.

INTERSTITIAL CEMENTATION

Cementation of the grains of a sedimentary aggregate is both a process and a resultant; as the latter it constitutes an important property inherent in lithified sediments. An evaluation of this property must consider the *degree* of cementation, the *texture*, and the *composition* of the cement. As a property, cementation pertains only to sediments the detrital grains of which are for the most part in mutual contact. In cases wherein the major detrital particles are separated in the aggregate, the binding material is termed the *matrix* (rather than cement), an example of which is provided by a well known rock type in which quartz sand grains are "floating" in a finely crystalline limestone matrix, the quartz grains evidently having been deposited together with a lime mud.

The degree of cementation may vary all the way from an openwork condition exemplified by openwork gravels, in which the interstices are free of cement, to a "tight" or closed-work condition in which the cement completely fills the interstices. Degree of cementation may be roughly evaluated in terms of *good*, *fair*, and *poor*.

Cements are of two textural types: *crystalline* and *fragmental*. Crystalline-textured cements may be in the form of chemical precipitates, syngenetic or epigenetic, deposited in the interstices as either aggregates of individual crystals or as growths in optical continuity on the detrital grains of the same composition. Fragmental-textured cements are in the form of clayey or silty binding material which, at the time of accumulation of the sediment, collects in the interstices between the larger grains. An example of fragmental-textured cement is provided by certain basal Cherokee sandstone lenses in the subsurface of eastern Kansas, which consist of medium to coarse quartz sand cemented by clay, fine quartz silt, or other fine-grained binding material. This type of cement is an expression of extremely poor sorting as to size. A primary fragmental cement, such as fine-grained lime mud deposited in the interstices of quartz sand grains, may become crystalline-textured as a result of epigenetic recrystallization.

Cementing substances display a wide range of composition and may be grouped in the following categories: (1) clay minerals, (2) carbonate cements (including calcite, dolomite, siderite, barite, *et cetera*), (3) iron oxides, (4) aluminum oxides, (5) silicate cements (including the chlorites, zeolites, feldspars, epidote, *et cetera*), and (6) sulphide cements.

Cementation of crinoidal sediment.—The crinoidal limestone of this report displays good cementation by a crystalline-textured cement consisting of very finely crystalline calcite, represented by the dark gray to black-appearing material between the crinoid plates and quartz grains in the thin section photographs of Plate I, A, B. This sediment probably was deposited as an openwork fragmental sand later to be cemented by epigenetic calcite precipitation.

MASS TEXTURE OF AGGREGATE

Sedimentary rocks display two fundamentally different types of mass texture: (1) fragmental (clastic) texture, and (2) crystalline texture. In sedimentary rocks of crystalline texture, as in igneous rocks, the aggregate consists of a mosaic of interlocking crystals wherein the individual crystal particles acquire shape by crystallization in place. In fragmental-textured rocks, on the other hand, grain shape is detrital in origin, and the grains are not mutually interferent but are bound together by a cement or matrix.

Crystalline textures may originate in three ways. First, they may form by primary chemical precipitation in place, exemplified by travertine and certain evaporites. Second, and quantitatively more important, they may form by secondary recrystallization and cementation of original fragmental-textured sediments; examples of this mode of genesis are limestones, including finely crystalline and lithographic varieties originally deposited as clastic lime muds and coarsely crystalline varieties deposited as calcareous sands. Third, crystalline textures may originate in sediments of original fragmental texture by secondary precipitation (secondary growth) of cementing material on the surfaces of fragmental grains; this material, of the same composition as the detrital grains, is precipitated in optical continuity on them. In this way the voids of the fragmental sediment become filled with secondary growth material, and a mosaic of interlocking crystals (crystalline texture) is formed. This third genetic type of crystalline texture is well illustrated by what Tieje has termed *orthoquartzite*,[21] a quartz sandstone firmly and completely cemented by secondary quartz precipitated on and in optical continuity with the detrital quartz grains. This sedimentary type should be distinguished from truly metamorphic quartzite, which Tieje has designated as *paraquartzite*, formed by recrystallization under high temperature-pressure conditions.

Most sedimentary rocks, including limestones and dolomites, have been deposited as fragmental-textured aggregates. Thus crystalline texture is for the most part acquired, resulting from diagenetic and metamorphic changes, and is the ultimate destiny of most sediments. There is a tendency for crystalline-textured sediments to become more coarsely crystalline with the passing of time.

All of the eight fundamental attributes apply to fragmental-textured sediments; only the attributes of composition, size, shape, space arrangement, and fabric, however, pertain to crystalline-textured rocks. As indicated by Table III, description of the attribute of size involves two different sets of terminologies, one for fragmental and one for crystalline aggregates. It is usually difficult, if not impossible, to evaluate the attribute of grain shape in crystalline-textured rocks.

Mass texture of crinoidal sediment.—The crinoidal limestone of this report, now of coarse to very coarsely crystalline texture, was originally deposited as a fragmental coarse to very coarse crinoidal sand. Thus its crystalline texture

[21] A. J. Tieje, "Suggestions as to the Description and Naming of Sedimentary Rocks," *Jour. Geol.*, Vol. 29 (1921), p. 655.

has been acquired, resulting from calcite cementation and possibly recrystallization of the detrital calcite grains.

PACKING OF AGGREGATE

The property of *packing* represents the degree of density of arrangement of grains in the sedimentary aggregate. In other words, the greater the mass per unit volume of the uncemented sediment the higher the degree of packing. In the absence of cementation, the property of *porosity* is inversely proportional to packing.

Packing is a function of the attributes of size, shape, space arrangement, and fabric. It is independent of average or mean size but is inversely proportional to the sorting as to size; that is, the poorer the sorting as to size the higher is the degree of packing inasmuch as the finer grains tend to fill the interstices between the larger. Packing varies directly as the sorting as to shape, the more heterogeneous the shapes of the particles the lower the degree of packing. Another aspect of its relation to shape is that it is inversely proportional to the degree of sphericity; in other words, the more the grain shapes approach a spheroidal condition (class III) the poorer is the packing. The attribute of mutual space arrangement of grains in the aggregate also controls the property of packing (see discussion of this attribute). Finally, packing is related to the attribute of orientation or fabric in such a way that it varies directly as the tendency toward preferred orientation of the components; in sediments of random fabric there is poor packing.

POROSITY

Porosity is the property that pertains to the character and relative volume of the interstices of a sedimentary aggregate. Distinction is made between *total* and *effective* porosity. The latter is a measure of the interconnected voids, whereas the former considers all pore spaces, isolated as well as interconnected. In petroleum geology and ground-water hydrology effective porosity is the more important aspect. Total porosity may be defined as the ratio of the voids to the total bulk volume of the rock; this ratio, multiplied by 100, is the per cent total porosity.

The property of porosity is related to two other properties, to which it is inversely proportional: (1) the degree of packing and (2) the degree of cementation. Porosity, like packing, is a function of the grain attributes of size, shape, space arrangement, and fabric. It is important to note that porosity is independent of average or mean size; thus, with the same degree of cementation and packing (including the same relative sorting as to size) a fine sand may have the same porosity as a coarse sand.

Porosity of crinoidal sediment.—The crinoidal limestone of this report has an average effective porosity in the section sampled of approximately 7.2 per cent, the measurements having been made with a Clough porosimeter. The relatively low average effective porosity is due to the fact that calcite cementation has for

the most part closed the voids between the otherwise highly porous aggregate of crinoidal and quartz grains.

PERMEABILITY

Permeability is the sedimentary property that governs fluid flow through a porous aggregate. In ground-water hydrology and petroleum geology permeability is important because it controls the flow of water, oil, and gas through porous rocks. Whereas porosity determines the amount of fluid present, permeability controls the amount recoverable. Permeability may be defined operationally as the volume of fluid of unit viscosity which passes through a unit cross-sectional area in unit time under a unit pressure gradient; it is expressed in terms of the *darcy*, with dimensions $cm.^2$ A thorough discussion of the theory and methods of permeability measurement has been presented in a paper by Fancher, Lewis, and Barnes.[22]

Permeability is dependent on effective porosity; therefore, it is controlled by the properties which condition porosity, that is, by the degree of cementation and the degree of packing (in turn controlled by the attributes of size, shape, space arrangement, and fabric). Unlike porosity, however, permeability is a function of the average or mean size of the grains as well as the sorting as to size; the smaller the mean size the lower the degree of permeability. Thus, permeability is a function of all the attributes which determine packing and porosity (see discussion of packing) and *in addition* is a function of mean size of the grains.

E. SEDIMENTARY STRUCTURES

Sedimentary structures comprise the large-scale or mass features of sedimentary deposits. Unlike attributes and properties, which depend on the character and interrelationships of individual components, structures involve the relationships of masses or aggregates of components. Structures, such as stratification, mud cracks, and so forth, are conditioned by time and space (vertical and lateral) changes of discrete character in the fundamental sedimentary attributes. For example, stratification may be the resultant of discrete vertical (time) changes in composition, and (or) grain size, and (or) fabric.

Structures are of two temporal types: (1) *syngenetic*, that is, structures formed approximately with and at the time of deposition of the sedimentary aggregate; and (2) *epigenetic*, those formed after deposition and burial. The following outline presents a classification of sedimentary structures based on their character and their time and mode of genesis.

I. SYNGENETIC STRUCTURES
- A. Stratification
  - 1. Parallel type
  - 2. Cross-stratification type
- B. Organic Structures
  - 1. Bioherms ("reefs") of various types
  - 2. Biostromes of various types

[22] G. H. Fancher, J. A. Lewis, and K. B. Barnes, "Some Physical Characteristics of Oil Sands," *Pennsylvania State College Bull. 12* (1933), pp. 64–167.

- C. Markings
  - 1. Imprints of rain drops, *et cetera*
  - 2. Tracks, trails, and burrows
    - a. Made by organisms
    - b. Made by inanimate objects
  - 3. Ice-crystal impressions
  - 4. Wave and current marks
    - a. Ripple marks (aqueous and aeolian)
    - b. Swash marks
    - c. Rill marks
    - d. Beach cusps
- D. Contemporaneous Deformation Structures
  - 1. Tensional features (mud cracks)
  - 2. Compressional features, including folded and faulted structures caused by surficial thrust action of ice and other surface agents
  - 3. Gravitational features, including structures formed by sliding and gliding of sediments down sloping surfaces

II. EPIGENETIC STRUCTURES

- A. Solution Structures
  - 1. Stylolites
- B. Deformational Structures
  - 1. Compressional
    - a. Cone-in-cone
    - b. Deformation resulting from recrystallization
    - c. Differential compaction structures
    - d. Folds, faults, *et cetera*
  - 2. Tensional
    - a. Faults, joints, *et cetera*

A discussion of stratification structure is presented in the succeeding section, and organic structures are treated under the section on paleontologic analysis. The other types of structures need not be reviewed here inasmuch as they have been covered in numerous papers and texts. The crinoidal limestone of this report does not display much development of structures other than stratification, there being no discernible organic structures, markings, contemporaneous deformation features, solution structures, and so forth. Epigenetic deformational structures, however, are represented, inasmuch as strata of the Grand Tower and other Devonian and earlier formations of the southeastern Missouri region have been severely fractured and tilted by faulting.

STRATIFICATION

Definitions.—A *stratum* is defined as a layer, greater than 1 cm. in thickness, that displays continuous (non-discrete) variation in lithologic character and is visually separable from other layers above and below, the separation being determined by a discrete change in lithology, a sharp physical break in lithology, or by both. A *lamina* is similar to a stratum except that it is less than 1 cm. in thickness. The term *bedding plane* denotes the "plane" of separation between laminae or strata; it may represent the contact of lithologically different strata or laminae, without a sharp physical break, or it may represent a physical break resulting from a period of non-deposition (diastem) or erosion.

The term *bed* is somewhat loosely employed but usually denotes a unit of sedimentary rock, of lower than member or formation rank, composed of two or more strata or laminae that manifest some degree of lithologic unity. The

component layers may be of the same composition and texture or may consist of two or more related lithologic types.

There are several miscellaneous terms used in describing stratification structure. The term *band* is applied to a stratum or lamina conspicuous because it differs in color from adjacent layers; a group of layers displaying color differences is described as being *banded*. The term *seam* is reserved for layers of coal enclosed above and below by other types of sedimentary rock. The term *parting* denotes a lamina occurring between massive strata different in lithology from the parting itself. A *varve* is an annual layer containing a record of seasonal environmental variation in the form of lithologic change.

Types of stratification.—The types and origin of stratification have been described in a classic paper by Andree.[23] The following outline presents in modified form the essential features of Andree's classification plan.

- I. Physical Break (Diastem) *without* Apparent Lithologic Change
  - A. Cross-stratification type
  - B. Parallel-stratification type
- II. Lithologic Change *without* Apparent Physical Break (Diastem)
  - A. Parallel stratification type
    - 1. Gradational ("graded-bedding")
      - a. Cyclical (glacial-lake varves)
      - b. Non-cyclical
    - 2. Non-gradational stratification
      - a. Cyclical
      - b. Non-cyclical
- III. *Combined* Lithologic Change and Physical Break (Diastem)
  - A. Cross-stratification type
  - B. Parallel-stratification type
    - 1. Gradational ("graded-bedding")
      - a. Cyclical
      - b. Non-cyclical
    - 2. Non-gradational stratification
      - a. Cyclical
      - b. Non-cyclical

The *physical break* (diastemic) type of stratification, marked by sharp bedding-plane breaks, is the resultant of cessation of sedimentation with or without erosional scour. On the other hand, the *lithologic change* type of stratification results from discrete vertical (time) changes in one or more of the fundamental sedimentary attributes, from vertical changes in composition, and (or) size, and (or) shape, and (or) fabric, and so forth. In addition to being represented by vertical lithologic change in any one genetic type (preëxisting rock, chemical precipitate, organic, or volcanic), stratification may be represented by vertical change from one genetic type to another; for example, change from strata of preëxisting rock to organic origin, or from organic to chemical precipitate origin.

British geologists, especially E. B. Bailey,[24] have been more concerned with studies of graded-bedding than have geologists in the United States. The term *graded-bedding* should be used in describing sedimentary deposits each stratum

[23] K. Andree, "Ursachen und Arten der Schichtung," *Geol. Rundschau*, Vol. 6 (1915), pp. 351–97.

[24] E. B. Bailey, "New Light on Sedimentation and Tectonics," *Geol. Mag.*, Vol. 67 (1930), pp. 84–90.

of which displays a gradation in grain size from coarse below to fine above. Thus, a sandstone with graded-bedding may be composed of strata, each of which grades from coarse sand at the bottom to fine sand at the top, or from fine sand at the bottom to silt at the top, and so forth. The bedding planes between gradational strata of this type are marked by rather abrupt lithologic (size) change and may or may not be marked by sharp physical breaks (diastems).

Thickness of layers.—This important aspect of stratification must be evaluated in petrographic analysis. Stratified deposits may be classified in four descriptive categories on the basis of the thickness of their layers.

1. *Fissile*, if deposit consists of laminae less than 2 mm. in thickness
2. *Shaly*, if stratification is in form of laminae from 2 to 10 mm. in thickness
3. *Flaggy*, if layers are in form of strata from 10 to 100 mm. in thickness
4. *Massive*, if strata are greater than 100 mm. in thickness

Thickness differences of layers in a vertical section of a given deposit should be described, as should also lateral variation in thickness of individual layers. Deposits of certain environments are composed of layers of nearly identical thickness in vertical section; other environments produce layers of different thickness, which may alternate in cyclical pattern or may show random vertical thickness variation. The neritic environment of epeiric seas tends to produce layers of marked uniformity in thickness over large areas, whereas other environments, such as river channel, deltaic, and littoral, produce sediments the layers of which show little vertical similarity and lateral continuity in thickness.

Form of bedding surfaces.—Bedding surfaces may be even, that is, in the form of regular planes; or they may be irregular—undulating, ripple-marked, wave- and current-marked, hummocky, and so forth. If they are irregular, details of form and dimensions of features should be described. With relation to each other, bedding planes may be parallel, non-parallel, convergent, and so forth.

Initial dip.—This aspect of stratification represents the angle of slope of bedding surfaces at the time of deposition, the contacts between layers usually being approximately parallel with the surface of deposition unless subsequently altered by differential compaction or other deformational processes. Initial dip may vary in degree from horizontal or a low angle up to the angle of repose for the sedimentary material in question. It is of particular significance in description of cross-stratification structures such as those in dunes and deltas, in description of strata flanking reefs or bioherms, volcanic masses, and so forth.

Stratification of crinoidal sediment.—The crinoidal limestone described in this paper has parallel stratification of the type involving physical breaks (diastems) without apparent lithologic change. The crinoidal strata vary in thickness from flaggy to massive, averaging approximately 1 foot (massive), and tend to be uniform in thickness in their lateral extent. The bedding surfaces are even, and little if any initial dip is represented.

F. LITHOLOGIC TYPE

The stratigraphic record is characterized by recurrence in time and space of lithologic and environmental *types*. *Lithologic classification* is more fundamental

than and should be prerequisite to stratigraphic classification; little attention, however, has been directed to this field and there is no unanimity of usage. As pointed out by Tieje, there is an urgent need for simple *common names* which may be used to designate lithologic types and to represent their mode of genesis and their environment of deposition. The new stratigraphy must include a breakdown of the stratigraphic record into lithologic types and their varieties and must provide widely acceptable lithologic common names.

Some lithologic names already are in widespread use; examples are provided by the terms arkose, graywacke, novaculite, clay ironstone, chalk, bentonite, travertine, tufa, tripoli, and coal. It still remains true, however, that our three most commonly used stratigraphic terms, *shale*, *sandstone*, and *limestone*, have little lithologic meaning when standing alone. The term *shale* is only of structural significance; it tells nothing of the composition, grain size, *et cetera*, of the rock inasmuch as shales may consist of clay minerals, limestone, quartz siltstone, fine sandstone, and so forth. Similarly, the term *sandstone* is of little more than grain-size significance; it fails to indicate the composition, structure, *et cetera*, of the rock inasmuch as sandstones may have shaly structure and may be composed of quartz, glauconite, and other minerals or rock fragments. Furthermore, even limestones, such as the crinoidal limestone of this report, may represent sandstone deposited as fragmental-textured sandy sediment later to be altered to crystalline texture. The term *limestone*, like sandstone and shale, is of limited lithologic significance, referring only to composition. Thus, it seems that the three lithologic names most widely employed in stratigraphic description have diverse petrographic implications, one based on the attribute of composition, another on the attribute of grain size, and a third on stratification structure.

Crinoidal limestone constitutes a fundamental lithologic type especially characteristic of a number of mid-Paleozoic stratigraphic divisions of North America. Tester[25] has suggested that the common name *criquina* be assigned to this lithologic type. The crinoidal limestone described in this paper occurs in a finely crystalline limestone and sandstone *association* in the Devonian Grand Tower formation of Missouri and Illinois, and it displays quartzose, glauconitic and heavy-mineral varietal features. The same lithologic type occurs in numerous other stratigraphic associations; that is, it is associated with numerous other lithologic types. For example, crinoidal limestone occurs as thin beds in the Hamilton shale sequence of central and western New York where it likewise shows distinctive varietal features. The type is also prominent where it flanks and dips away from the reef cores in the reef division of the Traverse beds of eastern Michigan and in the reef division of the Onondaga limestone of western New York and Ontario; in this reef associationship it shows distinctive varietal characters in that it is very coarse-grained, contains an abundance of detrital bryozoan fragments, and so forth. Numerous other association examples could be cited.

[25] A. C. Tester, *Guide Book Ninth Annual Field Conference Tri-State Geological Association* (1941), p. 6.

III. Paleontologic Analysis

In their studies of fossil assemblages paleontologists have been primarily interested in taxonomy and the description of species. Little attention has been given the ecologic aspects of the faunal assemblage picture. Paleontologic analysis should include description of those features of the fossil population which provide information for environmental interpretations; such features are treated in the following sections (A-D).

At the present time there is urgent need for quantitative studies of fossil populations, not only with regard to ratios of different species and classes but also with regard to size distributions, growth form variations, and other morphologic features. Statistical methods and approaches that might be employed in this new field of *paleobiometry* are presented in the book *Quantitative Zoölogy* by Simpson and Roe.[26]

A. Biocoenosis and Thanatocoenosis

The work of marine biological stations has shown that marine organisms exist as ecologic communities, known to ecologists as *biocoenoses*. The biocoenosis concept also applies, of course, to fresh-water and terrestrial organic communities. A *biocoenosis* has been defined by Hesse, Allee and Schmidt as an "association of living things which inhabit an environmentally uniform division of the biosphere and correspond in the selection and number of species with the average external habitat conditions."[27] The members of a biocoenosis are dependent on each other and are in a state of biological balance which is self-regulating and fluctuates about a mean. Some biocoenoses lack a plant foundation and are therefore for the most part dependent on the outer world for their food supply; others form virtual closed systems and are nearly self-sufficient. The Devonian crinoid-coral community, a record of which is contained in the crinoidal limestone of this report, must have depended largely for its food supply on abundant pelagic life wafted to it by marine currents.

The paleoecologist must make a clear mental distinction between a biocoenosis or *life assemblage* and a thanatocoenosis or *death assemblage*. The term thanatocoenosis was introduced by Wasmund[28] and is applied to a death association of organic remains, the components of which were either brought together after death or remained on the scene of their former life. As shown by the diagram of Figure 6, all fossil assemblages have passed through the thanatocoenotic stage inasmuch as they represent remnants of ancient death assemblages. Thanatocoenoses are of three general types (see Fig. 6).

[26] G. G. Simpson and A. Roe, *Quantitative Zoölogy*. McGraw-Hill Book Company, Inc., New York (1939).

[27] R. Hesse, W. C. Allee, and K. P. Schmidt, *Ecological Animal Geography*, p. 137. John Wiley and Sons, Inc., New York (1937).

[28] E. Wasmund, "Biocoenose and Thanatocoenose," *Archiv. f. Hydrobiologie*, Bd. 17 (1926), pp. 1–116.

1. Those composed largely of biocoenotic elements, that is, remains of organisms which lived on the scene and thus record the local environment of deposition; the fossil assemblage of the crinoidal limestone which this paper describes illustrates this type
2. Those composed of both biocoenotic (local) elements and foreign elements brought in from other environments, the latter having been transported in either after death or before to die on the site of accumulation of the sediment
3. Those composed primarily of foreign elements derived from other environments and biocoenoses; this type tells little if anything about the environment of deposition of the sediment in which it occurs and is illustrated by black shale assemblages of planktonic graptolites and by assemblages of pelagic protozoan remains such as Globigerina ooze

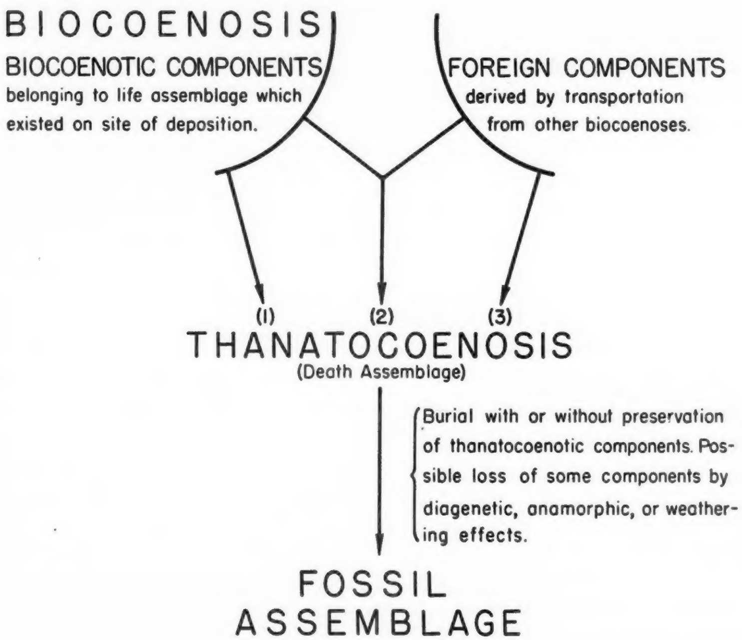


FIG. 6.—Diagram illustrating three thanatocoenotic types; and relationship between biocoenosis, thanatocoenosis, and fossil assemblage.

During life an organism is restricted to certain ecologic conditions and is thus representative of its environment, but after death its remains enter the mechanical realm or the chemical realm (are dissolved). In the mechanical realm the remains either stay in place (sedentary) or are transported in the same manner as are inorganic sediments. These transported remains or organic sediments may ultimately come to rest in deposits of environments to which the organisms are in no way related. As pointed out by Twenhofel,[29] many organisms live, die, and are buried under the same environmental conditions, but others die and are buried far from their place of life and may be entombed neither where they lived

[29] W. H. Twenhofel, *Principles of Sedimentation*, p. 153. McGraw-Hill Book Company, Inc. New York (1939).

nor died. In restoring the environment of a given deposit and its fossil assemblage a paleoecologist must isolate and consider the *biocoenotic species alone*.

B. CHARACTER OF BIOCOENOSIS

Component organisms of a biocoenosis have certain fundamental attributes which should be described and evaluated; these attributes also apply to fossil components of an extinct biocoenosis and should be considered in paleontologic analysis. The organic attributes are analogous to the previously described attributes of component grains of a sedimentary aggregate. The morphologic type (class, genus, and species) is more or less analogous to the sedimentary attribute of composition (mineral species, *et cetera*); the attribute of growth form is somewhat analogous to the sedimentary attribute of component shape; and so forth. The organic attributes are treated in Table IV and in succeeding sections of this paper.

The character of the original life assemblage represented by fossil remains in the Grand Tower crinoidal limestone are described in Table IV. The crinoidal debris, although transported to some extent, undoubtedly was derived from the immediate environment and does not represent foreign material brought in from other environments; this is strongly indicated by the fact that some of the columnals have remained together in the form of undissociated stem sections and by the fact that crinoidal remains constitute the major portion of the deposit. Therefore, it seems that crinoids were part of the biocoenosis; in fact, they must have represented the dominant morphologic type.

The crinoidal limestone of this report does not lend itself readily to paleontologic analysis inasmuch as the coral, brachiopod, and other remains are poorly preserved in the coarsely crystalline rock. Furthermore, the fauna has not as yet been extensively sampled and studied. Table IV presents only a rough, preliminary picture of the life assemblage, and the paleontologic analysis phase of the present report is thus incomplete.

Morphologic composition.—The taxonomic position (class, genus, species, *et cetera*) of a given organism or fossil is its most important descriptive attribute and is rather analogous to the attribute of composition (mineral species, *et cetera*) of sedimentary components. When considered from the viewpoint of the aggregate of organisms of a biocoenosis, this attribute calls for a faunal and floral list naming the morphologic types present in terms of species and (or) genera and giving their relative abundance in the total population. Relative abundance may be estimated in the field by simple counting and ratio-computing methods and expressed in terms of the following arbitrary percentage classes: less than 1, 1–5, 5–15, 15–30, 30–50, 50–70, 70–90, and greater than 90. The morphologic types present in the fossil population of the illustrative crinoidal sediment are listed in Table IV simply in terms of genera; more extensive sampling and study at a later date will permit species designation.

Internal structure.—This attribute is important in taxonomic description but

is not discussed here inasmuch as it is not particularly significant from the environmental viewpoint.

TABLE IV

CHARACTER OF BIOCOENOSIS REPRESENTED BY FOSSIL REMAINS IN ILLUSTRATIVE CRINOIDAL SEDIMENT

*Morphologic Type**	*Per Cent*	*Size*	*Growth Form*	*External Condition*	*Space Arrangement*	*Orientation*
TABULATE CORAL COLONIES *Favosites hemisphericus*	1–5	Diameter, 6–10 cm.; height, 4–12 cm.	Variable colony shapes	No signs of wear or breakage; poorly preserved	Tendency toward clustering of colonies along horizons	Upright, in life position; unmoved
INDIVIDUAL CUP CORALS *Heliophyllum sp.* Zaphrentids (several species) *Cystiphyllum americanum*	1–5	Calicular diameter, 2–5 cm.; height, 4–8 cm.	Variable cup shapes: conical, curved trochoid, irregular	No signs of wear or breakage; poorly preserved	Random; commoner along certain horizons	Random; upright to prone with axes trending in various directions
CRINOIDS Dissociated remains unidentifiable	70–90	Small size; columnal diameter, ½–3 mm.		Mostly dissociated to individual plates. Some columnals still together in form of stem sections	Omnipresent, random	
BRACHIOPODS *Atrypa reticularis* *Spirifer* (several species) Fragmentary evidence of other genera	1–5			Unbroken; no signs of wear; poorly preserved	Random; common along certain horizons	Probably unmoved and in life position
TRILOBITES *Phacops sp.*	–1	Length approx. 5 cm.		Very poorly preserved		
PELECYPODS AND GASTROPODS (fragmentary evidence)	–1					

* Extensive faunal collecting and study will expand this list and permit species designation.

Size.—Size is an attribute of an *individual* of a species as well as of a species *population* (aggregate) and is significant in environmental interpretation. Size and its evaluation are presentable in terms of a size-frequency distribution, which carries with it the aspects of *range* of variation and *average* size of a given species. Large range denotes poor size sorting and small range good sorting, these measures being ecologically significant.

Dwarf species are indicative of abnormalities of environment, with regard to such factors as salinity, temperature, turbidity, dissolved gases (*H_2S et cetera*),

and others well summarized in Shimer's paper on dwarf faunas.[30] As pointed out by Shimer, there are two types of dwarf faunas: (1) faunas in which the individuals are of smaller size than that which the species normally exhibits and are thus stunted; this is the resultant of an abnormal, unfavorable habitat, and (2) faunas in which all the individuals are small but of the normal size for the species represented; in this case selective factors have weeded out the large species.

The second type of dwarf fauna defined above involves another aspect of the attribute of size; that is, that one must consider not only the size distribution of each species in the aggregate but also the size distribution of the aggregate or biocoenosis itself. For example, some biocoenoses, such as those associated with reefs in the Onondaga limestone of western New York, are composed almost entirely of large, heavy-shelled species, whereas other biocoenoses, such as those represented in the calcareous shales of the Hamilton group, tend to be composed largely of small, thin-shelled forms. Thus the *aggregate size* concept is one which is extremely significant to the ecologist.

Growth form.—The attribute of growth form is important in ecologic studies because it may reflect the impress of environment on the morphology of organisms. Certain taxonomic groups, such as corals, show much more individual variation in growth form than do other groups. For example, the Paleozoic rugose coral genera *Heliophyllum* and *Cystiphyllum* display an amazing amount of growth form variation which is to a large extent indicative of the environmental setting in which the corals thrived. Colonial corals likewise show environmental morphologic differences, well exemplified by the genus *Favosites* which abounds in and adjacent to the Onondaga limestone reefs of western New York. The same species of *Favosites*, occurring both in the reef cores and in the detrital beds flanking and dipping away from the reefs, tends to show contrasted growth forms in these different but adjacent environments. In the reef cores, where upward growth was unhindered, the colonies tend to display a high domal outline, the height in some cases exceeding the basal diameters. In the crinoidal limestone flanking beds, however, where upward growth was smothered by organic detritus swept from the reefs, the colonies stand as broad, low tabular bodies, ranging up to several feet in diameter and but a few inches in thickness.

Like the attribute of shape of sedimentary particles, growth form is an attribute of an *individual* as well as of an *aggregate* of individuals belonging to a species. In the latter case, the factors of sorting, range of variation, and average condition enter the growth-form picture. Some species may in the aggregate show good sorting as to growth form; that is, they have a small range of variation. On the other hand, certain species evince poor sorting and have a wide range of form; in this case it is important that the paleoecologist record the average or most typical condition as well as the range of variation.

Other organic attributes.—Three other biocoenotic attributes of importance in environmental interpretation are treated in Table IV; they are: (1) external con-

[30] H. W. Shimer, "Dwarf Faunas," *Amer. Naturalist*, Vol. 42 (1908), pp. 472–490.

dition of the shells and other hard structures with respect to wear, breakage, healing, and so forth, (2) space distribution or arrangement within the aggregate of the different morphologic types, and (3) orientation (fabric) of the shells with respect to the bedding planes and compass direction. These ecologically significant attributes have been largely ignored by paleontologists and call for detailed study and description of the type carried on by sedimentologists on the analogous sedimentary attributes.

Population and fossil density.—The density concept, employed by ecologists working with living populations, is a valuable tool in environmental restoration and may be applied to ancient biocoenoses represented by fossil remains. The population density of a biocoenotic area is a measure of the total mass of animal substance present and is determined primarily by the available food supply. Each area has the greatest mass of life that it is capable of producing and supporting. Two environmentally different areas having different organic assemblages but quantitatively similar food supply conditions will ordinarily have population densities of the same order of magnitude.

The population density of an ancient environment is difficult to ascertain from fossil evidence inasmuch as some environments do not allow total incorporation within the stratigraphic record of remains of their plant and animal life, the remains being transported elsewhere or destroyed in place. Some rock types almost devoid of fossil remains may have been associated, in the environment of deposition, with a high population density; thus, *fossil density* is not an accurate measure of *population density* but in most cases presents a crude quantitative picture of the life assemblage. Fossil density is expressed in per cent and represents the proportion of the total rock aggregate which is composed of organic remains. The crinoidal phase of the Grand Tower limestone has a fossil density of approximately 85 per cent.

Class and species densities.—In biocoenotic analysis population density should be distinguished from class and species densities, the latter two representing a measure of the number of taxonomic classes and species in the biocoenosis. Whereas the amount of available food determines the population density, class and species densities are determined primarily by other ecologic factors, such as salinity, temperature, and character of the substratum. Optimum conditions with respect to these factors favor speciation and permit high species and class densities. High densities imply poor environmental sorting as to the taxonomic classes and species represented, whereas low densities imply good environmental sorting. These densities may be evaluated in terms of the number of species and classes present in the organic assemblage under consideration.

Stratigraphic application of density concept.—A survey of the faunal assemblages of the stratigraphic record strongly suggests that application of the concept of densities to the study of faunal assemblage types may provide information pertinent to environmental restoration. The stratigraphic record affords numerous examples of interesting density relationships. For example, certain of the

coral biostromes in the Hamilton group of western and central New York show high fossil (population) density, low class density, and medium to high species density, in that they are composed almost entirely of numerous species of corals. Examples of such Hamilton coral biostromes are provided by beds in the Centerfield member at several localities and by a bed in the Windom shale member in the vicinity of Leicester and Geneseo, New York.

A further illustration of the density concept is provided by the *Cystiphyllum* beds in the reef division of the Onondaga limestone of western New York and Ontario; these biostromes are composed almost exclusively of but one species of the rugose coral genus *Cystiphyllum* and may be described as having high fossil (population) density and low class and species densities. On the other hand, certain calcareous beds in the Hamilton shales of western New York display low fossil density, and high class and species densities. Finally, some deposits, such as the Jeffersonville limestone in the Falls of the Ohio district, display high densities from all three points of view.

C. ORGANIC STRUCTURES

Organic structures are of two types: (1) bioherms or "reefs" and (2) biostromes. The essence of these structures is that they consist for the most part of untransported remains of sedentary organisms. The illustrative crinoidal sediment of this report shows no organic structure (bioherms or biostromes), even though composed largely of organic remains, because the crinoidal debris is not in place but has been transported and deposited as a mechanical sediment.

The term *bioherm* has been defined by Cumings and Shrock so as to include "reeflike, moundlike, lenslike, or otherwise circumscribed structures of strictly organic origin, embedded in rocks of different lithology."[31] Bioherms vary greatly in size and shape and as to types of constituent organic remains. They may be composed in part or entirely of algal colonies, coral colonies, stromatoporoid colonies, crinoid remains, brachiopods, and so forth. The Tepee Buttes in the Pierre shale represent small bioherms composed of mollusc shells, the pelecypod *Lucina*. Thriving oyster bioherms are situated at the mouth of the Newport River, North Carolina. As illustrated by Laudon and Bowsher,[32] crinoid bioherms may be of great size.

Some organic structures of biohermal type are small, ranging down to a few feet or even a foot or less in diameter and height. These miniature bioherms consist of masses of organic remains embedded in lithologically different rocks and may be composed of bryozoans, crinoids, brachiopods, small corals, gastropods, and other fossil types; some are composed of but one fossil type whereas others represent a hodge-podge composite of several types. Some miniature bioherms are globular in shape, in which case they are known as "ballstones."

[31] E. R. Cumings, "Reefs or Bioherms," *Bull. Geol. Soc. America*, Vol. 43 (1932), p. 333.

[32] L. R. Laudon and A. L. Bowsher, "Mississippian Formations of Sacramento Mountains, New Mexico," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 25 (1941), pp. 2126–29, 2140–44.

The term *biostrome*, according to the definition of Cumings,[33] includes "purely bedded structures, such as shell beds, crinoid beds, coral beds, *et cetera*, consisting of and built mainly by sedentary organisms, and not swelling into moundlike or lenslike forms. . . . " The bedded character of a biostrome thus distinguishes it from the lenslike bioherm. Many of the so-called "reefs" of the stratigraphic literature, including the famous coral "reefs" of the Falls of the Ohio region, are not truly reefs (bioherms) but are rather of the biostromal or bedded type. Biostromes may be composed of the remains of individual and colonial corals, algae, brachiopods, pelecypods, and so forth. Most coal beds belong in this category. Many organic deposits, including some shell beds, coquinas, and crinoidal limestones, are not true biostromes because of the fact that the organic remains represent transported detritus, not in position of original growth.

D. BIOCOENOTIC TYPE

The concept of biocoenotic type is analogous to the previously described concept of lithologic type. Just as a sedimentary deposit is an assemblage of sedimentary components representing a response to external conditions and to each other, so a biocoenosis stands as an assemblage of coexisting and ecologically related animal and plant species likewise representing a response to external conditions and to each other. At the present time there is need for a breakdown of fossil faunal and floral assemblages into generalized types. Paleontologists have long been concerned with taxonomic classification but have given little attention to classification of assemblages.

The crinoidal limestone of this report contains a *crinoid-coral-brachiopod* biocoenotic type which occurs in Devonian rocks in many regions. This does not imply that different manifestations of this type contain the same genera and species but only that similar morphologic classes are represented. The crinoid-coral-brachiopod type is commonly associated in mid-Paleozoic rocks with the crinoidal limestone or "criquina" lithologic type. Thus there is an environmental relationship between the life and lithologic assemblages.

Certain biocoenotic types, such as the one cited above, recur vertically and laterally in the stratigraphic record, and it would seem that they existed wherever their ecologic requirements were satisfied and no migration barriers obtained. From a narrow point of view a biocoenosis represents an acutal community or life assemblage inhabiting a restricted area at a given time; an assemblage thus restricted represents a *faunule*, that is, a local concrete expression of a biocoenotic type. From a broad viewpoint a biocoenosis is different in that it may recur in time and space in somewhat different forms. The different faunules differ with respect to the component species represented, with respect to ratios of species, to size and growth form of the species, and so forth. In spite of this variation, however, they retain a degree of unity and distinctiveness, which makes it possible to classify them as belonging to the same parent biocoenotic type. For example, dif-

[33] Cumings, *op. cit.*, p. 334.

ferent tide-pool localities of the New England coast have different *faunules;* these, however, have much in common and may be classified together as belonging to the tide-pool biocoenotic type.

IV. Sedimentary Petrogenesis

The interpretive study of *genesis* of sedimentary deposits is divisible into the various fields here outlined, and discussed in subsequent sections of this paper.

A. SEDIMENTARY ECOLOGY (Environmental Analysis)
  1. *Syngenetic phase,* dealing with the surficial environment of deposition and accumulation of a deposit
  2. *Progenetic phase,* dealing with the surficial environmental history of the components of a deposit *prior* to their incorporation in the deposit; this treats their history from the source site to the site of final deposition
  3. *Epigenetic phase,* dealing with the subsurface environmental history of the deposit subsequent to the time of deposition and incorporation in the stratigraphic record

B. SEDIMENTARY DYNAMICS (Processes and Resultants)
  1. *Syngenetic phase,* dealing with the surficial sedimentation *processes,* inorganic and organic, which are involved in the deposition and accumulation of a deposit and which determine its attributes, properties, and structures
  2. *Progenetic phase,* dealing with the gamut of sedimentation processes and resultants affecting the components of a deposit during their trek from point of origin to point of final accumulation and incorporation
  3. *Epigenetic phase,* dealing with the subsurface processes and resultants affecting the attributes, properties and structures of the deposit subsequent to the time of deposition and incorporation in the stratigraphic record; this includes the processes of diagenesis .anamorphism, and weathering

Four genetic controls.—The components of the sedimentary record owe their existence in a deposit to the functioning of four controls, the sequential operation of which is prerequisite to the presence of a component, inorganic or organic, in a sedimentary rock. These four controls are expounded in Figure 7.

There is a tendency on the part of stratigraphers to overlook one or more of these four controls. It is commonly supposed, for example, that similar sedimentary environments (control II) obtaining in different areas will lead to the genesis of similar rock types in these areas; that this supposition does not logically follow is indicated by the following illustration. It is a well known fact that silica present in marine waters is absorbed on clay particles during deposition of a mud or shale. If this be so, then it appears that the most favorable conditions for true silica precipitation would obtain during a period of an abundant dissolved silica supply and clear, clay-free water; such conditions must have obtained during the deposition of the great Clear Creek chert section of the Devonian of the Mississippi Valley region. The question arises as to what would have happened in Clear Creek time if suspended clay had been available (control I) in the marine waters, all the other environmental factors (control II) remaining the same (weak currents *et cetera*). Would not a shale section have been deposited under the same environmental setting, the abundant silica being absorbed and deposited with the clay? Thus it would seem that by holding the environmental control constant and varying the supply control two entirely different rock types might be generated.

Another case in point is the accumulation, under similar environmental con-

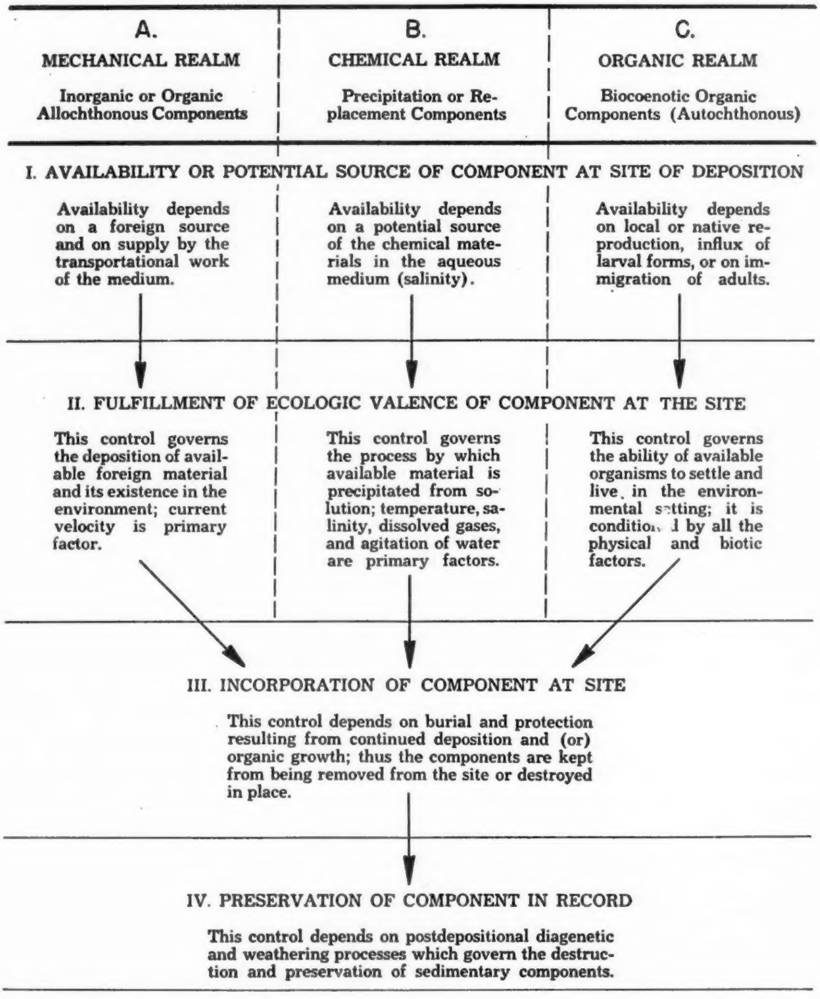


FIG. 7.—Four genetic controls governing existence of sedimentary components in a deposit.

ditions, of a coarse quartz sandstone and a crinoidal limestone, both of which might be cross-stratified and in general indicative of strong current conditions; in the one case terrestrial quartz sand is provided and in the other detritus from flourishing crinoidal growth. This citation provides a clear-cut illustration of a fundamental but seldom recognized sedimentational law: *the sea will tend to pro-*

duce, under given environmental (valence) conditions, sediments of similar textural character regardless of differences as to source and type of material being supplied. The expression *similar textural character* implies that the fundamental attributes, properties, and structures will be similar, excepting those which are functions of mineral composition.

A concrete stratigraphic expression of the quartz sandstone-crinoidal limestone relationship cited above is provided by the basal portion (Croneis' Bed 9)[34] of the Grand Tower limestone of central and eastern Missouri and southwestern Illinois; this stratigraphic division is believed to vary locally from practically pure crinoidal rock, to quartzose crinoidal limestone, to crinoidal quartz sandstone, to quartz sandstone (Dutch Creek sandstone). The particular phase of Bed 9 described in the present paper is from the Little Saline fault complex of eastern Missouri and represents a quartzose crinoidal *phase* of this system of contінous lithologic variation. Had crinoids failed to flourish on the scene, a quartz sandstone like the Dutch Creek would have been the resultant. This fact indicates that the supply or availability control (I) is the determinative one in the Bed 9 system of lithologic variation; the environmental control (II) probably was rather constant throughout the area of basal Grand Tower deposition.

The supply or availability control likewise is functional in the organic realm and, as indicated in Figure 7, is dependent on local reproduction, influx of larval forms, or immigration of adult forms. Just as there may be barriers to the dispersal of sediments in the sea, so may there be barriers to the dispersal of organic species, and these may be of several types. Actual geographic barriers probably are most effective in limiting organic migration and distribution, but others also may operate, such as areas with unfavorable conditions as to temperature, salinity, and other physical factors as well as biotic factors. Furthermore, current conditions on which larval forms are largely dependent for their distribution, may rule out the introduction of species to ecologically favorable areas where they would thrive if the availability control were functional. Paleontologists, in their studies of distribution of fossils and correlation, commonly fail to consider the possibility of the effects of these positive or negative barriers. Two separated but *ecologically similar* areas, on the same time horizon, may have different biocoenotic populations (different species and genera) because of availability (control I) differences alone. In spite of these superficial differences the two populations should be morphologically and structurally analogous inasmuch as the same rule cited above for sediments applies equally to organisms: *under given environmental conditions the sea will tend to produce organic assemblages of similar nature* (*similar biocoenotic type*) regardless *of differences as to species and genera available.*

Control III, that of *Incorporation*, is of vital significance in that it governs the induction of components into the stratigraphic record; if it fails to function, the components are either removed from the environment of deposition or destroyed on the site. Increased current velocities during times of storm may remove com-

[34] Croneis, *op. cit.*

ponents from the environmental scene and thus prevent incorporation. There are many environments, teeming with life, in which the conditions are such that organic remains are not incorporated and protected. As pointed out by Twenhofel,[35] wherever bottom conditions favor the existence of organisms which eat mud and bore into shells, all remains are apt to be broken and ultimately reduced to powder. Organisms which accomplish this work of destruction include certain boring sponges, annelids, fishes, crabs and other crustaceans, and some bivalves, echinoids, and holothurians. Incorporation is best accomplished in environments in which deposition or growth of organisms is extremely rapid or in which the bottom is unfavorable for scavengers and borers, the latter being true of environments of deposition of black shales. The low fossil (population) densities of most black shales is due to unfavorable environmental conditions for life (control II) and not to the incorporation control, which in this case operates favorably.

The *Preservation* control (IV) is the last in the sequence which conditions the existence of a sedimentary component. This control depends on the various diagenetic, weathering, and anamorphic processes by which components may be destroyed or altered in a subsurface environment. The preservation control is of vital importance to the paleoecologist engaged in restoring ancient life environments inasmuch as the character of a fossil assemblage is partially dependent on its diagenetic history. Fossil remains undestroyed by passage through the surficial and transitional realms (Fig. 8) are either obliterated in the subsurface realm or preserved by one of the several fossilization processes. Thus differences in the fossil assemblage of the same bed at two separate localities may not be due entirely to initial differences in the biocoenoses (controls I and II), or to incorporational differences (control III), but also may be due to different post-depositional (preservational) histories of the two areas.

A. SEDIMENTARY ECOLOGY (ENVIRONMENTAL ANALYSIS)

ENVIRONMENTAL REALMS

Environmental progression.—Through their cycle of existence the materials of the stratigraphic record progress through different environmental realms, and it is important that the paleoecologist understand and evaluate the impress of these realms on the sedimentary material he studies. The surficial or gradational realm, although having but brief jurisdiction over sedimentary materials, is nevertheless the most important in shaping the character and destiny of deposits. If an ancient surficial environmental setting is to be accurately restored from the study of a sedimentary rock, the student must first obtain a clear picture of the sediment as it appeared at the time of deposition and of its associated organic community. To do this he must isolate and describe the influence of each post-depositional environmental realm through which the sediment has passed. Primary and secondary lithologic characters, easily confused, must be clearly differentiated. It

[35] W. H. Twenhofel, "Environment in Sedimentation and Stratigraphy," *Bull. Geol. Soc. America*, Vol. 42 (1931), pp. 419–23.

is perhaps a truism that in some cases the rock materials studied in the field and laboratory have little in common with the sedimentary assemblage as it appeared at the time of deposition; similar primary assemblages may, as a result of different environmental histories, go to form contrasted rock types.

Figure 8 portrays in diagrammatic fashion the character and interrelationships of the various environmental realms, due cognizance being taken of the fact that nature draws few sharp boundaries.

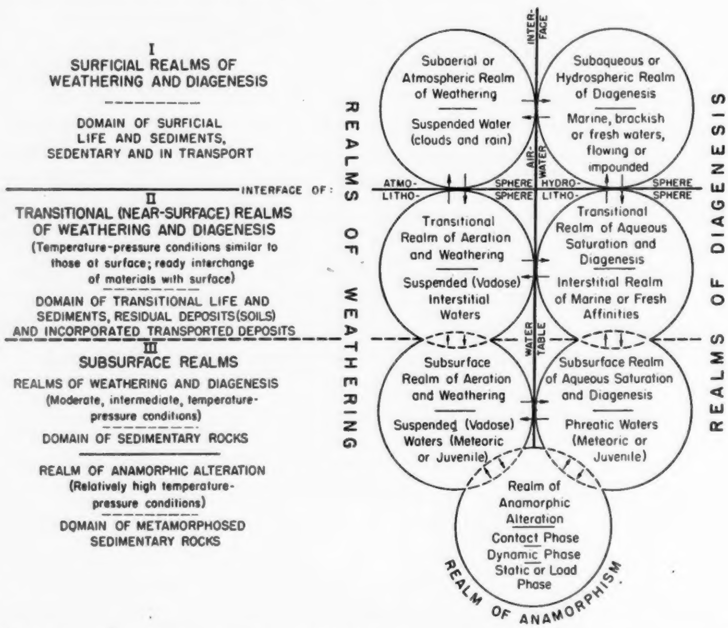


FIG. 8.—Environmental realms through which sedimentary materials may pass. Diagram has no depth connotation. High-temperature conditions, resulting in anatexis or melting in intrusive aureoles, cause sedimentary materials to leave the realms pictured and to enter the realm of fusion to form igneous rocks.

The environmental subdivision into realms is accomplished on a two-fold basis: (1) on whether the medium (interstitial or free) is dominantly water or air; and (2) on the temperature and pressure conditions. In realms II-A and III-A an interstitial *aerial* medium obtains (Zone of Aeration), these intergrading realms corresponding with Van Hise's "Belt of Weathering."[36] In realms II-B and III-B an interstitial *aqueous* medium is represented (Zone of Saturation), these realms corresponding to Van Hise's "Belt of Cementation."[37]

[36] C. R. Van Hise, "A Treatise on Metamorphism," *U. S. Geol. Survey Mon.*, Vol. 47 (1904), pp. 409–560.

[37] *Ibid.*, pp. 562–655.

Subsurface environmental factors.—The nature of subsurface environments and their impact on incorporated sediments comprise a little explored field of investigation in which detailed studies are urgently needed. The combination of environmental factors which influence a sedimentary component existing in a subterranean environment differs in certain respects from that which affects a component in a surficial environment. The subsurface factors are as follows.

1. Temperature conditions
2. Motion of interstitial water or air medium (sealed or stagnant *versus* free circulation conditions)
3. Chemical character of interstitial medium
   a. Salinity and dissolved gas content (O_2, CO_2, *et cetera*), if the medium is water. *pH*-value
   b. Chemical character of suspended water and gaseous character, if interstitial medium is air
4. Pressure of water or gaseous medium (hydrostatic pressure and air or gas pressure)
5. Stress conditions to which the rock components are subjected
6. Petrographic character of sedimentary material (attributes, properties, structures). Mineral composition, grain size, shape, fabric, *et cetera;* packing, cementation, porosity, and permeability
7. Character and activities of subsurface organisms, if present

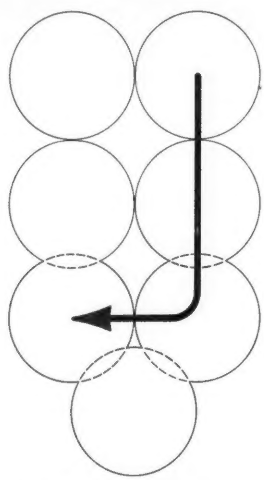


FIG. 9. Diagram of environmental history of crinoidal sediment, Bed 9, Grand Tower limestone, Ozora, Missouri.

Environmental progression (history) of crinoidal sediment.—Figure 9, patterned after Figure 8, pictures the environmental history of the illustrative crinoidal sediment, Bed 9, Grand Tower limestone of Ozora, Missouri. The surficial environment of deposition and accumulation of this sediment is described in succeeding sections of the paper, and the subsurface environmental history subsequent to deposition and burial is described in the section on Sedimentary Dynamics, in connection with the discussion of the epigenetic processes and resultants (diagenesis and weathering) which have affected the crinoidal sediment in the subsurface realms.

INTERPRETIVE RESTORATION OF SURFICIAL ENVIRONMENTS

Prerequisite to the analysis and reconstruction of an ancient surficial environment is a thorough understanding of the primary sedimentary assemblage and its associated organic community. Too often, paleontologists attempting to restore an ancient environment have had an inadequate understanding of the character of the sediment itself and have based their environmental interpretations solely on analogies between recent and fossil plants and animals and assemblages. A paleoecologist must be a sedimentologist as well as a biologist.

A cursory examination of the stratigraphic literature serves to suggest that environmental interpretations have followed no logical plan. Statements are made that a rock type is a beach deposit or a lagoonal deposit, or that it probably was laid down in deep water or under rough-water conditions, and so forth. These interpretations are valuable insofar as they are backed by thorough description and understanding of the rock type with regard to which they are made, but they present only a small part of the environmental picture. The following sections of this paper present a rigorous environmental breakdown into fundamental factors inherent in an environmental setting and provide a logical and organized plan of approach.

The concept of *surficial environment* has two different aspects: (1) an *ecologic aspect*, which pertains to the sum total of factors which influence an organism or sedimentary component existing at any point on the earth's surface, and (2) a *geographic aspect*, which pertains to the regional or space environmental relations of that point to the source and depositional provinces in general.

ECOLOGIC FACTORS INHERENT IN SURFICIAL ENVIRONMENTS

The factors listed in the following outline pertain only to subaqueous environments. Study of a subaerial environment would entail the listing and consideration of a related set of analogous factors, in which case the factor of salinity would drop out of the picture, the character of pelagic life would be replaced by that of flying organisms, and so forth. The factors which influence the existence of an organism or sedimentary component anywhere on the earth-water interface are as follows.

- I. Factors Pertaining to the Substratum
  - A. Composition and textural character
  - B. Inclination
- II. Factors Operative on Substratum
  - A. Movement (transportation) of sediment on substratum
    - 1. Individual
    - 2. Collective
  - B. Character and activities of benthonic life
- III. Factors Pertaining to the Medium
  - A. Motion of the medium
    - 1. Agitation (turbulence)
    - 2. Bottom currents (velocity)
  - B. Dissolved gas content
  - C. Salinity

D. Character of suspension load (composition, grain size, volume, turbidity, *et cetera*)
E. Temperature
F. Light intensity
G. Hydrostatic pressure

IV. Factors Operative in Medium above Substratum
A. Movement (transportation) of suspended sediment
B. Character and activities of pelagic life

Most of the ecologic factors are *dynamic* and in the present oceans show periodic, seasonal and diurnal, as well as non-periodic variations in time and space. For each factor, such as current velocity, it is important in restoring an ancient environment to evaluate both the *range* of variation and the *average* value. Most of the factors are more or less interrelated and represent dependent variables. Three independent variables, *temperature, salinity,* and *hydrostatic pressure,* determine the character and distribution of physical properties in the ocean. The paper by Fleming and Revelle[38] on physical processes in modern oceans should be consulted in the interpretive reconstruction of physical processes and factors obtaining in ancient seas.

Character of substratum.—This factor is of prime importance to the existence of many benthonic creatures. It includes the composition and textural attributes, such as the average and degree of sorting as to grain size of the bottom sediment and also includes properties such as the degree of cementation and lithification and the degree of packing and porosity. Composition of the substratum is important in the case of a subaerial soil substratum devoted to agricultural purposes.

Inclination of substratum.—This factor is significant in regions of marked relief of the surface of deposition, for example, delta environments, and reef margins. Sedimentary particles and unattached living organisms may exist on a highly inclined substratum if the slope does not exceed their maximum angle of repose.

Movement of sediment on substratum.—Tractional transportation of bottom sediment, whether in the form of individual or collective motion of the particles, is significant in the existence of benthonic creatures. It is well known that areas of shifting sands (collective movement) are extremely unfavorable for the development of bottom communities and are apt to be barren, organic deserts. This is true of most cross-stratified sandstones, such as parts of the Beauvais sandstone of Missouri, which bear but a sparse benthonic fauna. On the other hand, the fact that *individual movement* of sand grains does not ordinarily inhibit benthonic animal growth is evinced by the abundant bottom fauna of many parallel-stratified sandstones and crinoidal limestones, in the genesis of which the individual type of grain movement must have occurred.

Character and activities of benthonic and pelagic life.—In the categories of these two factors are included the biotic aspects of the environment. Of these, food supply is most important, a sufficient amount of organic food being an indispensable condition for the habitability of an area by animals. Organic associations and

[38] R. H. Fleming and R. Revelle, "Physical Processes in the Ocean," *Recent Marine Sediments, A Symposium*, Amer. Assoc. Petrol. Geol. (1939), pp. 48–141.

interrelationships and the struggle for existence also are part of the biotic picture, as exemplified by the failure of bivalves, mussels and clams, to thrive in an area dominated by starfish. The population density of the environment also should be considered. It is impossible for the paleoecologist to evaluate these biotic factors in other than a general way inasmuch as the zoöplanktonic food supply and organic interrelationships can not be interpreted from paleontologic evidence.

Motion of medium.—This factor includes directive currents and random agitation or turbulence and is of great significance especially in controlling the size character of sediments in an environment. Only *bottom current* conditions can be evaluated in the restoration of an ancient environment; they may be designated roughly in terms of centimeters per second with the use of Hjulstrom's size-velocity curves for erosion and deposition. From the study of the range of size of particles of a sediment it is possible to make a rough estimate of the range of variation in current velocity in the depositional environment. Current *direction*, as well as velocity, is a significant aspect which sometimes may be determined from a knowledge of regional stratigraphic relations, average direction of cross-stratification, and so forth.

Currents exert a powerful influence over an organic community in that they serve as a transporting agent for food, provide a means for immigration and emigration of larval forms, and in that they in some cases have a strong impact on growth form. Experiments performed on branching corals, for example, have shown that in shallow, strongly agitated water short stumpy branches are formed whereas quiet-water conditions permit the growth of long, slender fragile branches, both growth forms being manifested by the same species and even by parts of the same individual placed in the contrasted environmental settings.

Dissolved gas content.—This factor of an aqueous environment usually does not constitute a strong limiting factor inasmuch as oxygen, the most vital gas, is absent or nearly so in but few marine environments. In the stagnant depths of the Black Sea, however, and in many Norwegian fiords closed by a bar, the evolution of hydrogen sulphide has combined nearly all of the available oxygen, and such conditions probably existed in tracts of ancient epeiric seas. This factor may be evaluated in terms of highly aerobic, aerobic, anaerobic, and highly anaerobic. Highly aerobic environments, such as those of tide pools and shallow current-swept banks, commonly have a large organic population (density) and might be expected to produce dark sediments; on the contrary, light-colored sedimentary deposits are the resultant because of nearly complete oxidation of the organic matter. The converse relationship obtains in the case of anaerobic (reducing) environments.

Salinity.—The extent of salinity variation that can be endured by animals is different for different species. Some types, such as reef corals, are influenced by slight changes in salt content, whereas others can withstand wide variation. Present-day reef corals can endure a salinity range of from 30 to 40‰, higher concen-

TABLE V

ECOLOGIC ANALYSIS OF MARINE ENVIRONMENT REPRESENTED BY CRINOIDAL PHASE, GRAND TOWER LIMESTONE, OZORA, MISSOURI

Ecologic Factors		*Evaluation and Evidence*
Factors pertaining to substratum	Composition and textural character of substratum	Fragmental. Very coarse to medium sand composed of calcareous crinoidal débris and quartz. Admixture of very fine sand and silt composed of quartz, heavy minerals, *et cetera*
	Inclination of substratum	Rather level or horizontal surface maintained, as indicated by evenness of bedding surfaces, lateral uniformity of strata, and lack of noticeable cross-stratification
Factors operative on substratum	Movement of sediment on substratum (individual or collective motion of particles)	Individual movement (rolling, sliding, saltating) of larger components—medium to coarse crinoidal sand and quartz sand. Movement intermittent, effective during storms and times of strong current action. Movement indicated by introduction of quartz sand and by distribution of crinoidal débris in strata of uniform thickness. Lack of cross-stratification and bedding irregularities suggests no collective movement
	Character and activities of benthonic life	Densely populated crinoid-coral plantation. Dominantly small crinoids, with admixture of tabulate corals, cup corals, brachiopods, pelecypods, *et cetera*
Factors pertaining to medium	Motion of medium over bottom (turbulence and directive currents)	Variable current action. Poor size sorting indicates rather wide range of current velocity from strong to weak. Generally mild currents and wave agitation (turbulence) suggested by little worn and incompletely dissociated crinoidal débris. Intermittent strong action during storms. Periods of calm allow deposition of silt and fine sand from suspension. Hjulstrom's size-velocity curves suggest 30 cm. per second current necessary for moving coarse sand (crinoidal débris and quartz) and 0.2 cm. per sec. necessary for silt deposition
	Dissolved gas content	Aerobic conditions, varying with current strength, evinced by density of benthos with its high O_2 requirements
	Salinity	May have been normal marine to slightly concentrated (30 to $40^{\circ}/_{\circ\circ}$) as suggested by ability of living corals to withstand high but not low salinities. Density of shell life indicates large-scale turnover of *Ca* salts
	Character of suspension load (composition, grain size, volume, and turbidity)	Very fine sand and silt, mostly quartz and heavy minerals. Small volume (low turbidity). Intermittent suspension during times of strong current action. Current velocity moving coarse sand would keep fine sand and silt in suspension
	Temperature	At least moderately warm, with probable seasonal change. Warmth suggested by coral abundance and shallow water conditions
	Light intensity	Probably rather strong, because of coral abundance and large phytoplankton requirements
Factors operative above substratum	Movement of suspension load	Very fine sand and silt, moved intermittently during times of stronger currents and turbulence, must have settled to bottom during periods of calm
	Character and activities of pelagic life	Unknown. Large volume of microplankton, larval forms, *et cetera* suggested by large planktonic food demands of benthonic community and by reproduction

tration being more favorable than lower. Thus corals do not thrive off river mouths where marine water is freshened and salinity is abnormally low; they are known to thrive, however, in parts of the Red Sea where salinity is higher than in normal marine water. In addition to conditioning animal existence, the factor of salinity is important in serving as the source of chemically precipitated sediments as well as of organically precipitated shells, tests, and so forth.

Character of suspension load.—The composition, grain size, and volume of suspended material affects organisms and bottom sediments. Turbidity of the medium may limit organic growth and make it impossible for certain species to inhabit an area. The suspension load constitutes a potential supply for bottom sediments, effective when the wind or water currents and turbulence fall below the critical velocity and contributing to building of such deposits as loess and marine shales.

Temperature.—This factor of the medium, of maximum importance to marine zoögeography, may be evaluated for an ancient environment only by uncertain analogies between living and fossil plant and animal types. For example, present-day reef corals flourish only in relatively warm water (mean temperature greater than 60°F.); fossil coral-reef structures of Paleozoic rocks suggest, by analogy, that the Paleozoic marine waters in which they were formed were relatively warm. In modern oceans water temperature varies with location (latitude and longitude) and with seasons, and there are indications that such was also the case in ancient seas. Deposits of halite, gypsum, and other evaporites suggest warmth of ancient water bodies.

Light intensity.—This usually does not function as a direct limiting factor for animal existence but ordinarily determines the development of plant life. Inasmuch as animals ultimately are dependent on plants for their food supply, this factor affects animals indirectly. Sedimentary deposits are affected by this factor insofar as they are composed of plant remains.

Hydrostatic pressure.—This factor does not exert a strong controlling influence on either organisms or sediments in relatively shallow water bodies such as those of epeiric seas. Pressure increases one atmosphere for every 10 meters of depth, and, except at great depths, plays an unimportant rôle in the life of marine animals other than certain fishes.

ECOLOGIC VALENCE CONCEPT

The concept of ecologic valence, expounded in the text by Hesse, Allee, and Schmidt,[39] is of paleontologic and stratigraphic import. Coexisting organisms and sedimentary particles are governed by the same set of afore-described ecologic factors; they are not tied hard and fast to unalterable values of these conditioning factors but rather can tolerate a range of variation. The composite of the factorial ranges constitutes the ecologic valence of an organism or sedimentary component.

[39] Hesse, Allee, and Schmidt, *op. cit.*, pp. 20–21.

For example, the valence of a coral species might be designated as follows: salinity 30–40‰ (parts per mille), mean temperature 60–85°F., current velocity less than 100 cm. per second, dissolved oxygen greater than 4.0 ml/L, light intensity greater than some measurable value, and so forth. Although such valence determinations are theoretically feasible, experimental studies have in general been made for only one or two measurable factors affecting a living species. Thus the valence concept is little more than a valuable aid to proper mental orientation in environmental studies.

If a species is to reside in a given environmental setting, that environment must satisfy its ecologic valence; that is, the latitude of variation of each of the factors must lie somewhere within the range tolerated by the species. Furthermore, the nearer the environment approaches the species' optimum for each factor, the more flourishing will be its existence. The more the factors depart from optimum values, the higher the degree of adaptation the species population must make and thus the less it will flourish. Forms that can not survive extremes must perish. In addition to being conditioned by physical factors of their environment, members of an organic community are also dependent on biotic factors, on plant and animal relationships, the struggle for food and energy, and so forth.

The factor for which a species has the narrowest range of tolerance acts as the limiting factor in its existence, regardless of the fact that the species may withstand a wide range with respect to the other factors. A counterpart of this rule is that the selection of species in a given environment is to a large extent determined by that habitat factor which most nearly approaches the viability minimum, this being known in ecologic circles as the *law of the minimum*. For example, there may be sufficient oxygen, favorable temperature, and abundant food supply in a salt-water pond, but the high salt content or salinity will permit the existence of only a few euryhaline animals.

An organic community or biocoenosis represents an assemblage of species whose ecologic valences overlap or are roughly coincident. Thus the valence of a biocoenosis itself is a composite of the valences of the component species. Unless altered by biotic factors a community type tends to be coextensive in time and space with the maintenance of similar physical conditions. There are numerous illustrations indicating that communities in widely separated parts of the world may be similar if similar ecologic conditions obtain. Any permanent time or space change in the physical or biotic factors of an environment bring about a change in the composition and character of a biocoenosis. Some members of the community drop out, others thrive better than before, foreign species may enter; growth forms of some species may undergo alteration, size distributions may change, and so forth. In these ways the community strives toward equilibrium with its changing environment.

Sedimentary components, like organisms, are governed by the factors of their environment and have an ecologic valence. The influence of the different factors

on organisms and sedimentary grains, however, differs markedly. Such factors as temperature and light intensity, of importance to the existence of organisms, have little direct influence on sedimentary components. Of significance to chemically precipitated sediments and readily soluble components are the factors of salinity, temperature, motion or agitation of the water, and dissolved gas content. On the other hand, little soluble and relatively inert clastic components, such as quartz, are dependent primarily on the factor of motion of the medium (current velocity and turbulence). A lithologic type tends to show but little character variation throughout time and space provided there is maintenance of similar factorial conditions. Any permanent time or space change in the environmental factors causes lithologic changes. When the range of current velocity of the environment of a clastic deposit, such as quartz sand, is shifted in the direction of higher velocities, the sand assemblage undergoes a change; small grains out of equilibrium with respect to the new size-velocity range are swept away, and larger grains may be added to the deposit. In these and other ways the sedimentary community, like the organic community, strives to approach equilibrium with its changing environment.

GEOGRAPHIC ENVIRONMENTAL FACTORS

In the geographic analysis scheme here propounded the various geographic factors are classified in three categories: (1) physiographic factors, (2) diastrophic factors, and (3) gradational factors. These factors pertain to the regional or space relations of a given environmental setting and to the source and depositional provinces in general.

Depositional province and subprovince.—As here employed, the term *depositional province* denotes the areal extent of a region of continuous and related sedimentation, such as the Eastern Interior basin during Middle Devonian time. Within the confines of such a province several distinct but environmentally related lithologic types may be undergoing simultaneous sedimentation, the restricted areal extent of any one lithologic type constituting the *subprovince* of that type.

Source province and subprovince.—The concept of source province, as here employed, embraces the areal extent of a positive region undergoing reduction and contributing preëxisting rock components for the building of sedimentary deposits. During Middle Devonian time Ozarkia and Appalachia were the dominant source provinces in eastern North America. The term *source subprovince* denotes a restricted area of the general source province and embraces the areal extent of all preëxisting rocks, igneous, sedimentary, and metamorphic, which contribute components via transportation routes for the building of the deposit in question.

Outline of geographic factors.—Following is an outline classification of the geographic environmental factors.

I. PHYSIOGRAPHIC FACTORS
  A. Depositional Subprovince
    1. Character of depositing medium
    2. Geographic place represented
      a. Location
      b. Areal extent
      c. Shape and degree of enclosure
    3. Attitude and topographic relief of depositional surface
    4. Depth of bottom below water surface, in case of subaqueous environment
    5. Distance from shore or boundary of source province
  B. Source Subprovince
    1. Geographic place represented
      a. Location
      b. Areal extent
      c. Shape or outline
    2. Attitude and topographic relief of erosional surface
    3. Elevation above sea-level
II. DIASTROPHIC FACTORS
  A. Depositional Province and Subprovince
    1. Structural type (trough, basin, shelf, *et cetera*)
      a. Location
      b. Areal extent
      c. Shape or outline
    2. Rate and magnitude of diastrophic movement
      a. Orogenic subsidence
      b. Epeirogenic subsidence
  B. Source Province and Subprovince
    1. Structural type (dome, arch, geanticline, shield, *et cetera*)
      a. Location
      b. Areal extent
      c. Shape or outline
    2. Rate and magnitude of diastrophic movement
      a. Orogenic emergence
      b. Epeirogenic emergence
III. GRADATIONAL FACTORS
  A. Depositional Subprovince
    1. Agents and media of transportation
    2. Modes of transport
    3. Rate and volume of transport
    4. Distance and direction of transport from boundary of source province
    5. Position of depositional surface with regard to base level or profile of equilibrium
    6. Rate and volume of deposition, accumulation, and incorporation
    7. Continuity of sedimentation (diastems *et cetera*)
  B. Source Subprovince
    1. Lithology of source rocks
    2. Climate and type of weathering
    3. Agents and media of transportation
    4. Modes of transport
    5. Rate and volume of transport
    6. Distance and direction of transport
    7. Position of erosional surface with regard to base level or grade (stream age)
    8. Rate and volume of erosion, land reduction and removal of sediment

PHYSIOGRAPHIC FACTORS

Character of medium.—The various types of depositional media are as follows.

I. AQUEOUS
  A. Impounded Water Body
    1. Without oceanic connections (lake)
    2. Marine
  B. Running Water
    1. Confined surface (streams)
    2. Open surface (sheet wash *et cetera*)
II. AEOLIAN
III. GLACIAL

Geographic place.—The geographic place represented by the source or depositional subprovince may be described with little difficulty for present-day environmental settings. It is difficult and often impossible, however, to evaluate this factor for ancient environments which are not so self-evident and must be interpreted from our slim knowledge and understanding of the stratigraphic record.

Geographic place names of impounded water bodies include, for example, estuary, fiord, epeiric shelf sea, epeiric interior sea, lake delta, and marine swamp. Geographic places represented in running water environments include river flood plain, valley bottom, delta, piedmont slope, and alluvial fan. Geographic place designations also may be applied to aeolian and subglacial environments.

The location, areal extent, and shape and degree of enclosure of the source and depositional province and subprovince can best be described by means of a paleogeographic map such as that of Figure 10.

Depth of water.—In an impounded water medium the physiographic factor of *depth* is important inasmuch as it conditions such ecologic factors as character of the substratum, temperature of the medium, hydrostatic pressure, salinity, dissolved gas content, and light intensity. A picture of depth conditions in present-day impounded water bodies, epeiric seas, continental shelf seas, lagoons, and lakes, has been presented by Barrell.[40] Table VI is modified from one in Barrell's paper.

TABLE VI

AVERAGE DEPTH CONDITIONS IN PRESENT-DAY IMPOUNDED WATER BODIES
(Modified from table by Barrell)

Type of Water Body	*Distances from Shore, in Miles*				
	5	10	20	80	100
	Depths of Water, in Feet				
Stormy epeiric seas	55	70	90	110	110
Quiet epeiric seas	35	50	70	90	90
Wide lagoons	15	15	—	—	—

Quiet epeiric seas are represented by the shelf sea east of the Mississippi delta and by the Persian Gulf. The latter is an epeiric sea with a central unfilled portion below wave base. Stormy epeiric seas are represented by Lake Erie and the North Sea, in both of which full depth of water is attained within 100 miles from shore, as far as wave action is concerned.

Ancient epeiric seas typically were very shallow water bodies. Inasmuch as such shallow-water features as ripple marks, cross-stratification, and mud cracks often occur at the same horizon over areas covering thousands of square miles, their development must not have been restricted to near-shore environments but

[40] J. Barrell, "Rhythms and the Measurements of Geologic Time," *Bull. Geol. Soc. America*, Vol. 28 (1917), pp. 776–85.

evidently could take place anywhere on the epeiric sea bottom. Widespread marine silts and sands of the ancient epeiric seas indicate the effectiveness of wave action in agitating the bottom material and working it by oscillatory action to great distances. From the foregoing evidence, and others, depths of 20 to 50 or 100 feet may be regarded as typical of Paleozoic epeiric seas.

FIG. 10.—Paleogeographic map of time represented by Grand Tower limestone deposition. Dot and arrow indicate position of subprovince of crinoidal phase of Grand Tower.

Physiographic (regional) environment of crinoidal sediment.—A physiographic analysis of the Middle Devonian regional environmental setting in which the illustrative crinoidal limestone was deposited is presented in outline fashion.

I. PHYSIOGRAPHIC FACTORS
- A. Depositional Province and Subprovince
  1. *Character of depositing medium.* Impounded water body (marine)
  2. *Geographic place.* Depositional province—epeiric sea occupying Eastern Interior basin (see paleogeographic map of Figure 10). Subprovince of crinoidal sediment situated near Ozarkian shore of epeiric sea in southeastern Missouri
  3. *Attitude and topographic relief of depositional surface.* A marine basin flat of little relief; possibly some shoal tracts
  4. *Depth.* Shallow water (neritic zone), estimated as being in the order of magnitude of 25–100 feet; more probably 25–50 feet

5. *Distance from shore.* Subprovince of crinoidal sediment less than 10 miles from eastern shore of Ozarkia, possibly much less

B. Source Province and Subprovince
1. *Geographic place.* Landmass of Ozarkia, a positive tract (dome) probably connected with land to southwest (see paleogeographic map, Figure 10). That the Ozarkian land area of Middle Devonian time represented the source province is suggested by regional stratigraphic relationships (Fig. 11). Middle Devonian sediments of preëxisting rock origin decrease in volume or entirely disappear outward from Ozarkia northward, northeastward, eastward, and southeastward
2. *Attitude and topographic relief.* A gently sloping surface with small erosional relief
3. *Elevation above sea-level.* Low to moderate

The subprovince of the crinoidal sediment must have been rather localized, occupying a small tract off the northeastern shore of Ozarkia (Fig. 10), inasmuch as the lower Grand Tower crinoidal limestone phase grades laterally into quartz sandstone southeastward and eastward (Dutch Creek sandstone and Hoing sandstone) and northwestward (sandstone phase of Mineola formation). The exact extent of the subprovince of this lithologic type is difficult if not impossible to determine because of structural complexities and paucity of outcrops and well logs and samples.

DIASTROPHIC FACTORS

Diastrophism is the major geologic process, the functioning of which produces surface irregularities and sets the counteracting process of gradation in operation. The sedimentational processes are but part of the major process of gradation which tends toward the development of a plane surface. If it were not for diastrophism, the earth's surface equilibrium would not be disturbed by rising and sinking movements, and sedimentation therefore would not function; thus diastrophism is the ultimate cause of the development of sedimentary deposits.

It follows from the foregoing reasoning that the character of a sedimentary deposit (attributes, properties, structures) is largely governed by the character and degree of diastrophism obtaining in the source and depositional provinces during its genesis. Diastrophic conditions vary between two extremes. Although there are all stages of intergradation, the conditions in a given area may be classified as belonging to one or the other of two fundamental types: (1) *orogenic,* and (2) *epeirogenic.* Conditions may be intermediate between these two extremes, and the sediments will then show mixed characteristics.

Orogenic type of diastrophism and sedimentation.—The orogenic type of diastrophic movement is characterized by large-scale and rapid movement. *Positive* orogenic movements result in rapid and high elevation of a region, attended by erosional dissection and rapid reduction; reduction, however, does not keep pace with emergence. *Negative* orogenic movements result in rapid subsidence of a region (trough or basin), attended by rapid accumulation of thick sections of sediments. The orogenic type of diastrophism and resulting sedimentation may in turn be subdivided into two contrasted types: (1) the tensional or block-fault type exemplified by diastrophic movements and sedimentation in the Basin-and-Range province during Tertiary time and in the area east of the Appalachians during Triassic and Jurassic time, and (2) the compressional type, exemplified by

the Alpine orogeny with its flysch and molasse phases of sedimentation. Thick sections of orogenic sediments accumulate in the troughs and are eroded from the rising geanticlines.

Sediments deposited by continental glaciers and by streams draining therefrom commonly show orogenic characteristics. Such sediments are *pseudo-orogenic* in character; that is, they are deposited in regions of epeirogenic movements of the earth's crust under glacial conditions.

Epeirogenic type of diastrophism and sedimentation.—This is characterized by small-scale and slow movement, unattended by pronounced faulting and folding. *Positive* epeirogenic movements result in slow elevation of a region, dome or arch; inasmuch as erosion and reduction almost keep pace with uplift, high mountains are not formed. Examples of positive epeirogenic tracts are the Ozark dome and the Cincinnati arch, which underwent slow emergence during part of Paleozoic time. *Negative* epeirogenic movements result in slow subsidence of a region, basin or trough; inasmuch as sedimentation and accumulation almost keep pace with subsidence, more of a structural than a topographic basin or trough is formed. An example of a negative epeirogenic tract is the Eastern Interior basin during much of Paleozoic time.

Diastrophic environment of crinoidal sediment.—The outline which follows describes the regional Middle Devonian diastrophic conditions under which the Grand Tower crinoidal limestone phase (Bed 9) was deposited.

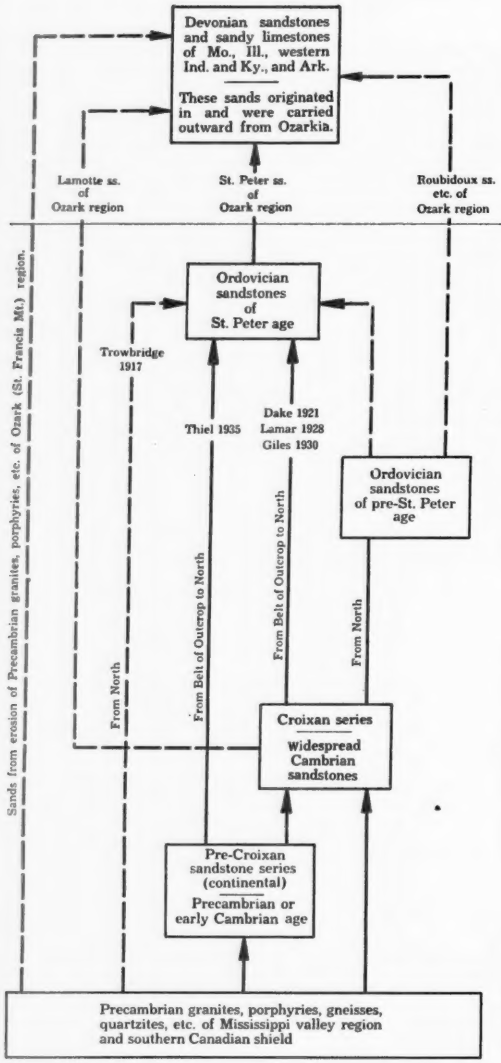
II. DIASTROPHIC FACTORS

- A. Depositional Province and Subprovince
  1. *Structural type.* A structural basin (Eastern Interior basin) occupying southeastern Missouri, southern half of Illinois, western Tennessee and Kentucky, and Indiana. Subprovince of crinoidal sediment situated near western margin of basin, where it joins the Ozarkian positive province
  2. *Rate and magnitude of diastrophic movement.* Slow epeirogenic subsidence of intermittent and differential character
- B. Source Province and Subprovince
  1. *Structural type.* A structural dome (Ozark dome); see map of Figure 10
  2. *Rate and magnitude of diastrophic movement.* Slow epeirogenic emergence of intermittent character

GRADATIONAL FACTORS

Gradation is the major geologic process by which the irregularities of the earth's surface, produced by diastrophism, tend to become smoothed to produce a plane surface. The array of gradational factors are listed in the foregoing outline of geographic environmental factors and are discussed in the following paragraphs. Those pertaining to epeiric sea environments, including equilibrium profile and wave-base control, are admirably discussed and illustrated in Barrell's classic paper on "Rhythms and the Measurements of Geologic Time."[41] A picture of probable depth conditions of the epeiric seas may be gleaned from Barrell's paper, and it expounds the often forgotten law that *subsidence is the ultimate basis of deposition, accumulation, and incorporation of sediments.*

[41] Barrell, *op. cit.*, pp. 776–809.



S.W. ILL. AND W. KY.	SOUTHEASTERN MISSOURI	CENTRAL MISSOURI
	Basal ss. beds of St. Laurent ls.	Sandstone phase of Callaway ls.
	Beauvais sandstone	Auxvasse Creek ss.
Sandstone beds of basal Grand Tower ls. Dutch Creek ss. (Pendleton and Hoing ss.)	Sandy limestone phases of Grand Tower ls.	Sandstone phase of Mineola fm.

MO., ARK., & SOUTHERN ILL.	IOWA, MINN., WISC., & ILL.
Thebes ss.	
St. Peter ss.	St. Peter ss.
Everton ss.	

MISSOURI, ARKANSAS	IOWA, WISC., AND ILL.
Sandstone beds of Powell, Cotter and Jefferson City formations	Sandstone beds of Shakopee formation
Roubidoux ss. Gunter ss.	New Richmond ss.

MO., ARK., & SOUTHERN ILL.	IOWA, MINN., WISC., & ILL.
	Madison ss.
	Devils Lake ss.
	Jordan ss.
	Mazomanie ss.
	Franconia ss.
	Dresbach ss.
Lamotte ss.	Eau Claire ss.
	Mount Simon ss.

The vast supply of sand reworked through formations listed above was generated for the most part during the late Precambrian or early Cambrian, a time of continental peneplanation and drastic chemical decay followed by a thorough mechanical attack by rivers, wind, and littoral agencies, forming river, dune, beach, littoral, and neritic sands.

MAIN AVENUES OF SEDIMENTATION

POSSIBLE ALTERNATIVE OR ACCESSORY AVENUES WHICH MAY HAVE FUNCTIONED

FIG. 11.—Flow diagram showing probable progress of sedimentation of early Paleozoic sands (quartz and associated stable minerals) in Mississippi Valley district. Diagram shows possible sources of terrestrial (preëxisting rock) sand material in crinoidal phase (Bed 9) of the Grand Tower limestone.

Lithology of source rocks (source analysis).—Genetic study of a sedimentary rock containing allochthonous components derived from preëxisting rocks must include an interpretive synopsis of the probable source rock or rocks which yielded these allochthonous components to the transporting agents. Krynine's pioneering work[42] in this field might well serve as a guide for students concerned with problems of source analysis. Source studies should if possible treat the *ultimate* as well as the *immediate* source of the preëxisting rock components. The ultimate source of most of the stable component grains is, of course, an igneous rock, and its determination may not be an easy task, especially if the components have progressed through a number of sedimentary cycles. A flow diagram (Fig. 11) helps in obtaining a mental picture of the history or lineal descent of sedimentary components and presents both the probable source rocks by stratigraphic divisions and the probable areas of derivation.

The rock type or types which have served as source material for the building of a sedimentary deposit may be revealed by interpretive study. Study of the mineral composition of a sediment usually shows a certain suite of mineral species which individually or collectively may be suggestive of the source rock or rocks. An understanding of probable mineral associations is helpful in diagnosis, and an understanding of the regional stratigraphy and petrography of all potential source rocks is prerequisite to a sound source analysis. The more diversified the rocks of the source subprovince, the more varied is the character of the descendant deposit; few deposits derive their components from a single preëxisting rock type. Source rocks of mineral species commonly occurring in sediments are described in the mineral outlines of Milner's text on sedimentary petrography.[43]

Climate and type of weathering.—Certain detrital mineral species are highly indicative of the climate and type of weathering obtaining in the source province from which they were derived. It is important to note the degree of alteration of minerals. An abundance of fresh feldspar grains in a deposit is indicative of mechanical weathering under rigorous desert, glacial, or tropical monsoon conditions of high relief; whereas altered feldspar grains are indicative of chemical weathering in humid areas of little relief.

Weathering of the chemical type is accomplished by the processes of solution and katamorphic alteration—carbonation, oxidation, hydration, and hydrolysis. Mechanical weathering is the resultant of abrasive work of running water, ice, and wind, and the disintegration work of plants and animals, frost action, and insolation.

Gradational analysis, environment of crinoidal sediment.—Gradation conditions in the Middle Devonian regional environment of the crinoidal phase (Bed 9) of the Grand Tower limestone are here described in outline fashion.

[42] Krynine, *op. cit.*, pp. 78–87.

[43] H. B. Milner, *Sedimentary Petrography*, 3d ed., pp. 229–357. Nordeman Publishing Company (1940).

III. GRADATIONAL FACTORS
- A. Depositional Subprovince
  1. *Agents and media of transportation.* Transport by weak to moderate marine currents
  2. *Modes of transport.* Tractional transport of crinoidal débris and medium to coarse quartz sand; suspension transport of silt and very fine sand composed of quartz, tourmaline, *et cetera*
  3. *Rate and volume of transport.* Probably slow rate and small volume except during storms
  4. *Distance and direction of transport from boundary of source province.* Unknown. Probably less than 50 miles in a direction somewhere between northeastward and southeastward, depending on location of river mouth from which preëxisting rock components were derived
  5. *Position of depositional surface with regard to base level.* Depositional surface generally at base level or wave base—somewhat above during storms and below during periods of calm
  6. *Rate and volume of deposition, accumulation and incorporation of sediment.* Small volume and relatively slow rate indicated by dominant organic source and admixture of subordinate amount of derived preëxisting rock material
  7. *Continuity of sedimentation.* Accumulation intermittent with diastems represented; this is suggested by discrete vertical changes in faunal content and by sharp physical breaks in stratification without apparent lithologic change
- B. Source Subprovince
  1. *Lithology of source rocks.* Sand and silt material of terrestrial (preëxisting rock) origin for most part derived from St. Peter sandstone of Ozark region (Fig. 11). This is suggested because quartz grains and heavy mineral suite (Pl. I), including tourmaline, rutile, magnetite, and glauconite, are similar to those of St. Peter. St. Peter source also suggested by stratigraphic relationships in Ozark region which indicate the St. Peter sandstone was undergoing erosion during Middle Devonian time. As shown by Figure 11 there are three other possible sources of quartz and heavy-mineral grains in crinoidal rock: (1) Ordovician sandstone beds of Powell, Cotter, Jefferson City, Roubidoux, and Gunter formations of Ozark region, (2) Cambrian Lamotte sandstone of Ozark region, and (3) sands from erosion of pre-Cambrian granites and porphyries of St. Francis Mountain region, this last source being improbable because of high degree of rounding of material
  2. *Climate and type of weathering.* Unknown. Warm climate suggested by abundance of corals in adjacent seas. Humid conditions with chemical weathering suggested by presence only of stable derived minerals in crinoidal sediment; lack of unstable minerals may, however, be due to the fact that the derived grains had been reworked through several sedimentary cycles
  3. *Agents and media of transportation.* River currents
  4. *Modes of transport.* Tractional transport of medium to coarse quartz sand; suspension transport of silt and fine sand
  5. *Rate and volume of transport.* Probably slow rate and small volume except during floods
  6. *Distance and direction of transport.* Unknown. Probably less than 100 miles in a direction somewhere between northward and eastward, depending on location of rivers and drainage
  7. *Position of erosional surface with regard to base level or grade.* Can not be interpreted from available evidence. Large volume of quartz sand in Middle Devonian beds (Fig. 11) equivalent to the Grand Tower limestone crinoidal phase suggests that at this time the Ozarkian source province was not at grade but was in youthful or early maturity stage of erosional cycle
  8. *Rate and volume of erosion, land reduction and removal of sediment.* Relatively slow rate and small volume under epeirogenic conditions

B. SEDIMENTARY DYNAMICS (PROCESSES AND RESULTANTS)

The dynamic aspect of sedimentary petrogenesis is strongly related to the environmental aspect inasmuch as it deals with the processes and resultants (changes) by which sedimentary deposits and their components tend to become adapted to, or to be brought into equilibrium with, their changing environments. The dynamic aspect is subdivided into two fields of study: (1) sedimentation, which pertains to the processes active on the surface, and (2) subsurface (epigenetic) processes and effects.

SEDIMENTATIONAL ANALYSIS

The term *sedimentation*, as here employed, refers to the dynamical aspects of gradation; that is, it pertains to processes active on the earth-water or earth-air interface which bring about leveling of surface irregularities by distribution and reallocation of surficial materials. The field of sedimentation is divisible into three phases.

1. *Reduction* of topographically positive areas above base level of erosion by *initial* erosion (beginning of new sedimentary cycle); removal of material in solution or by mechanical transporting agencies
2. *Transportation*, including *temporary* erosion and deposition in transit; sedimentary particles ordinarily come into motion (are eroded) and come to rest (are deposited) many times in their trek from source site to site of final accumulation and incorporation
3. *Accumulation* of sediment in topographically negative areas below base level of deposition; *final* deposition and incorporation

TRANSPORTATION

Mobility of sedimentary components and organisms is of major importance in the environmental picture and plays a significant rôle in sedimentary petrogenesis. Reconstruction and description of the environment and genesis of a sedimentary deposit must include an analysis of the components with regard to both their probable *mode* of transport and deposition and the *agents* and *media* responsible for their transportation and deposition. Such a transportational analysis is exemplified by Figure 13.

A sedimentary deposit may be heterogeneous with respect to the transportational histories of its components; that is, the deposit may represent an assemblage of components of different transportational histories, different in regard to the agent and (or) the mode of transportation and deposition. Such heterogeneity is typical of many deposits of the stratigraphic record. On the other hand, some deposits are highly homogeneous in this respect.

Agents and media of transportation.—These may be outlined as follows.

- I. SUBAERIAL AGENTS (Air Medium)
  - A. Gravity directly (rock avalanche *et cetera*)
  - B. Air currents and turbulence (wind)
  - C. Organisms
- II. SUBAQUEOUS AGENTS (Marine, Brackish, or Fresh-Water Medium)
  - A. Gravity directly (submarine mud-flow *et cetera*)
  - B. Water currents and turbulence
    - 1. In impounded body (currents generated by convection, tides, or wind)
      - a. Lake
      - b. Marine body
    - 2. In running water body
      - a. Stream or river currents
      - b. Sheet wash
  - C. Organisms
- III. SUBGLACIAL AGENTS (Ice Medium)
  - A. Ice currents (lamellar flow)

Motion of the medium.—In painting an environmental picture the paleoecologist must consider and evaluate the factor of *motion of the medium*. According to Fleming and Revelle,[44] the motion of a water particle may be divided into two

[44] Fleming and Revelle, *op. cit.*, p. 77.

parts: first, local agitation involving random or turbulent and reciprocating or wave motion; and second, mean or current motion. Turbulent eddies and wave motion alone do not result in net transport; current motion, however, is characterized by a certain uniformity of velocity and, when combined with turbulence, results in net transport in a definite direction.

It is possible to make a rough quantitative estimate of the velocity of motion of the medium by consulting Hjulstrom's size-velocity curves for erosion and deposition previously mentioned. The crinoidal limestone of this report contains transported components up to 3 mm. in mean diameter, which indicates that the mean velocity of the medium during its deposition must have at times been in the order of magnitude of 30 cm. per second, at least. Among other size classes,

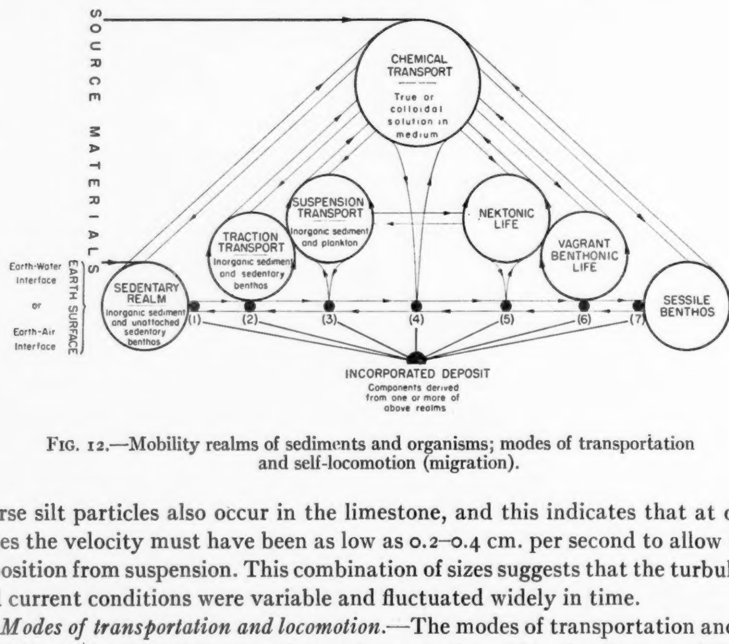


FIG. 12.—Mobility realms of sediments and organisms; modes of transportation and self-locomotion (migration).

coarse silt particles also occur in the limestone, and this indicates that at other times the velocity must have been as low as 0.2–0.4 cm. per second to allow their deposition from suspension. This combination of sizes suggests that the turbulence and current conditions were variable and fluctuated widely in time.

Modes of transportation and locomotion.—The modes of transportation and the mobility realms of sediments and organisms are pictured in the diagram of Figure 12 and outlined in the following paragraphs. The lines and arrows connecting the various realms emphasize the possibility of interchange or transfer of materials. For example, some pelagic creatures are at certain times *nektonic* or free-swimming and at other times *planktonic*, in suspension and dependent on movements of the water. Other examples of transfer are provided by fine sand grains in traction transport, which enter the suspension realm during times of increased current velocity; and pebbles in the sedentary realm entering the realm of traction transport under more rapid current conditions. On death, organic materials leave

the life realms, and the remains either enter the mechanical (traction or suspension) realm or the chemical realm (are dissolved), or they may remain *in situ* and go to form sedentary organic deposits.

Physical (mechanical) realms of transport.—In these realms mobility of components is dependent on motion of the medium (fluid mechanics) and mechanical laws. The relationship between size and mode of transport in an aqueous medium is suggested by Table VII. If the current velocity is insufficient to move a given component, whether an unattached living benthonic organism or a lifeless sedimentary component of inorganic or organic origin, that component is said to be *sedentary*. Examples of deposits composed largely of sedentary components include residual soils, lag gravels, and oyster biostromes.

TABLE VII

Relationship between Size and Mode of Transport*

Mode of Transport	*Size of Component*
Gravity traction fall (landslides, *et cetera*)	Massive blocks Boulders Cobbles
Traction in water currents (6th-power law)	Pebbles Granules Coarse sand
Inertia suspension in water currents (6th-power law)	Medium sand Fine sand
Viscous suspension in water (Stokes' law)	Coarse silt Fine silt
Colloidal suspension or solution in water	Clay Colloidal particles
True solution in water	Ions

* Relationship between size and mode of transport, as indicated by spacing of size classes at right, is generally used and varies with current conditions. For example, under certain conditions cobble and boulder-size components may be carried in traction transport, coarse sand components may be carried in suspension, *et cetera.*

The realm of *traction transport* likewise includes unattached living benthonic organisms and lifeless sedimentary components of inorganic or organic origin. Traction movement may occur solely in the form of *individual motion* of particles (rolling, sliding, or saltating), or may occur in the form of collective motion (dune or ripple phase, smooth phase, or antidune phase). Examples of deposits composed for the most part of traction-transported components include coarse quartz sandstones and crinoidal limestones, and stream and beach gravels.

The realm of *suspension transport* carries living planktonic organisms and lifeless sedimentary grains of inorganic or organic origin. Suspension may be in the form of inertia suspension (6th-power law) or viscous suspension (Stokes' law). Deposits composed largely of suspension-transported and deposited grains include loess, clay shales, *Globigerina* ooze, and so forth.

Chemical realm of transport.—In this realm mobility is dependent on motion of the medium and chemical laws pertaining to true and colloidal solution and precipitation. Organic precipitation brings about transfer of material from the chemical to the life realms. Inorganic deposition may be in the form of primary chemical precipitates, such as gypsum, halite, and other evaporites, or chemical replacements, such as phosphorite and some cherts and dolomitic limestones, or may be in the form of colloidal precipitation (coagulation and flocculation). As indicated in Figure 12, chemical precipitation may occur directly on the substratum or may occur up in the medium, in which case the precipitated grains enter the suspension realm of mechanical transport and either settle to the bottom or are carried away to be deposited elsewhere.

Life realms of self-locomotion (migration).—In these realms mobility is for the most part independent of motion of the medium, although influenced thereby, and is dependent on self-locomotion. In the *nektonic realm* of swimming creatures death brings about transfer of the organic remains to the mechanical transportation realm, and the remains either settle to the bottom and become incorporated or are carried away in suspension or traction transport. An example of a deposit composed largely of organic components from the nektonic realm is provided by fish-bone breccias.

In the *vagrant benthonic realm* locomotion is by crawling or walking, jumping (saltating), wriggling, or burrowing. On death, the remains enter the mechanical realm and are either incorporated on the death site or carried away in traction transport to be incorporated elsewhere. Trilobite and gastropod beds represent types of deposits composed of components from this realm.

The realm of *sessile or attached benthonic* creatures includes certain algae, corals, pelecypods, crinoids, and so forth. On death, the organic remains may enter the mechanical realms to form such lithologic types as cross-stratified crinoidal limestones or may remain *in situ* to form such sedentary organic deposits as algal and coral reefs, and brachiopod biostromes.

Erosion, transport, and deposition.—Mobility or transportation involves the operation of three processes: *erosion*, *transport*, and *deposition*. As pointed out by Hjulstrom,[45] erosion and deposition are integral parts of transportation inasmuch as individual particles usually come into motion (are eroded) and come to rest (are deposited) many times in their progress from source to place of final accumulation and incorporation. Rolling and saltation are the usual modes of traction transport, and sliding usually is of minor importance. According to Hjulstrom, size of the particles and roughness of the substratum strongly influence the nature of the motion. Large particles are more readily eroded by currents than small particles, partly because of their larger surface area and partly because of the fact that they stand up higher in the water where the motion is stronger.

Turbulence has a strong influence on sedimentary particles in that upward

[45] F. Hjulstrom, "Transportation of Detritus by Moving Water," *Recent Marine Sediments, A Symposium*, Amer. Assoc. Petrol. Geol. (1939), p. 13.

streams may cause them to pass easily from saltation movement to the suspension realm of transport, the substratum thus being eroded. Saltation may be depicted on the diagram of Figure 12 by a figure-8 circuit of the traction and suspension realms. Suspended particles have their own individual settling velocities; the position of the particles in the water is determined by the net effect of two opposing factors: the turbulent motion which causes the particles to rise and the force of gravity (settling velocity) which makes them sink. The factors influencing settling velocity have been studied by Wadell and include size, shape, and specific gravity of the particles and the specific weight, temperature and viscosity of the medium through which they settle. Particles of silt and fine sand size ordinarily are carried in suspension and belong in the traction realm only under very slow current conditions. Suspension transport does not greatly affect the particles, except by solution, inasmuch as there is little mutual contact.

If turbulence or velocity decrease is marked and sudden, the suspension and traction loads are deposited together, and sorting is then poor. Loads are deposited from both modes of transport on the basis of the size, shape, and specific gravity of the particles.

In the realm of chemical transport the colloidal phase carries such substances as ferric hydroxide, aluminum hydroxide, silica, certain clay minerals, and organic colloids. Colloidal particles do not settle in response to gravity, and their suspension does not depend on movements of the medium. They are precipitated (deposited) through flocculation or coagulation. In the true solution phase of chemical transport, erosion occurs by solution and deposition by precipitation, these processes resulting from changes of temperature or pressure, by changes of concentration, or by chemical reactions.

Effects of transportation.—In the case of autochthonous components genesis and deposition are simultaneous and synonymous. Allochthonous components, however, are more complex in that transportation intervenes between genesis and final deposition and institutes chemical and physical changes by the processes of solution, abrasion, chipping, and splitting. In this way the component parameters of size, shape, roundness, and surface texture are affected. The effects of transportation on sedimentary particles have been described by Russell.[46]

Because of the selective action of the transporting agent, a sedimentary assemblage in transport undergoes local and progressive sorting as to size, shape, and mineral composition, the latter being due to differences in specific gravity, hardness and resistance to solution of the different minerals. The effect of sorting is caused by *selective erosion* and *selective deposition* by water and air currents. Sorting as to size is dependent on current velocity and follows approximately the pattern of Hjulstrom's size-velocity curves for erosion and deposition.[47]

Transportational analysis of crinoidal sediment.—The transportational story

[46] R. D. Russell, "Effects of Transportation on Sedimentary Particles," *Recent Marine Sediments, A Symposium*, Amer. Assoc. Petrol. Geol. (1939), pp. 32–45.

[47] Hjulstrom, *op. cit.*, p. 10.

of the crinoidal phase (Bed 9) of the Grand Tower limestone is a fascinating one and is set forth in the tabular diagram of Figure 13. It is probable that the columnals and other crinoidal débris, which constitute the greater part of the rock and range up to 3 mm. in mean diameter, were carried only in traction transport; during times of lessened current velocity, periods of calm, they were sedentary. The same was true for the medium to coarse quartz sand grains (Pl. I); their space distribution in the rock aggregate coincides with and has the same random

TRANSPORTATIONAL TYPES OF COMPONENTS	TRANSPORTING AGENTS AND MEDIA (HISTORY)	MODES OF TRANSPORTATION (HISTORY)
Crinoidal debris (1/4 to 6 mm.)	Marine currents	Sessile Crinoids $\xrightarrow[\text{Dissociation}]{\text{Death}}$ Traction transport ⇅ Sedentary
Medium to coarse quartz sand (1/4 to 1 mm.)	River currents → Marine currents	(Varying with current velocity) Traction transport ⇅ Sedentary
Very fine to medium sand composed of quartz, tourmaline, limonite, etc. (1/16 to 1/4 mm.)	River currents → Marine currents	Suspension transport ⇄ Sedentary; Suspension transport ⇄ Traction transport; (Varying with current velocity) Sedentary ⇄ Traction transport
Silt composed of quartz, glauconite, etc. (1/256 to 1/16 mm.)	River currents → Marine currents	(Varying with current velocity) Suspension transport ⇅ Sedentary
Benthonic corals, brachiopods, etc. (See Table IV)	Unmoved by marine currents (autochthonous)	Sedentary benthos

FIG. 13.—Tabular diagram illustrating transportational analysis and history of components of the illustrative crinoidal sediments (see Pl. I).

pattern as that of the crinoidal débris. On the other hand, the medium to very fine sand and silt, consisting of quartz, tourmaline, *et cetera* (Pl. I, Table I), evidently were carried in suspension transport during storms and times of stronger current action. The reason for this belief is two-fold: (1) a current velocity (Hjulstrom curve) sufficient to move the larger quartz and crionoidal sand grains would carry the fine sand and silt in suspension, and (2) the fine sand and silt have an interesting space distribution in the rock aggregate, occurring in the form of patches, stringers, and bands (Pl. I, a, b) which suggests that they were deposited during times of quiet water, buried in the crinoidal débris, and not picked up with the return of stronger currents.

ACCUMULATION AND INCORPORATION

Little attention and study has been directed toward that phase of sedimentation pertaining to final deposition, accumulation and incorporation of sedimentary deposits. The concepts of base level, wave base, and profile of equilibrium thus far have had but little application to stratigraphic problems. An outstanding contribution in this field, as it relates to accumulation of sediments in epeiric sea environments, has been made by Barrell in the paper, previously cited, "Rhythms and the Measurements of Geologic Time."

Accumulation controlled by base level and subsidence.—The most important concept to be gleaned from Barrell's paper is that the rate and volume of permanent accumulation and incorporation of sediments in epeiric seas are determined not so much by the rate of supply as by the rate of subsidence of the surface of deposition. Sediment deposited at a given point ordinarily is only a small fraction of that which is carried past. Thus, in the long run, *accumulation is a function of subsidence*, which, as a rule, is differential in character.

Under orogenic conditions there tends to be large-scale incorporation of great thicknesses of sediments. This is due to relatively rapid and continuous subsidence, fewer diastems and disconformities, and larger supplies of sediments. In contrast to this epeirogenic conditions tend to bring about small-scale incorporation of relatively thin bodies of sediments, this resulting from slow and discontinuous subsidence, with many diastems and disconformities and smaller volumes of sediment supplied.

Wave base, as defined by Barrell, is that depth at which wave action ceases to be strong enough to erode bottom sediments. Above wave base the coarser bottom sediments, medium to coarse sands and gravels, are transported and deposited. These shallow-water sediments, in traction transport, frequently are eroded and deposited by wave and current action and are gradually moved toward an area wherein they may become permanently deposited and incorporated below wave base. Below wave base the bottom sediments are comparatively undisturbed and may be permanent, unless the bottom is brought above wave base. The finer sediments, including clays, silts, and fine sands, carried in suspension transport, are only deposited below wave base; products of this environment include clays, siltstones, shales and fine-grained limestones.

SUBSURFACE (EPIGENETIC) PROCESSES AND RESULTANTS

As a result of their dynamic impact, the subsurface environmental factors, previously described, control the operation of processes which may alter or obliterate certain components of a sedimentary aggregate in an attempt to keep it in equilibrium with its changing subsurface environments. In addition, new components, epigenetic in origin, may be added to the sedimentary aggregate. Thus the attributes, properties, and structures of a deposit may undergo alteration after burial. These processes, as outlined in Table VIII, operate with different degrees of rigor in the different subsurface environmental realms through which sedimentary materials may pass; the realms are portrayed in diagrammatic

fashion in Figure 8. Each realm is characterized by the relative competence and net results of the processes obtaining therein, some processes being of major importance and others of a secondary or minor degree of importance (Table VIII). The relative operational importance of the processes in any individual case depends to a large extent on the character of the rock materials affected.

TABLE VIII

SUBSURFACE PROCESSES BY WHICH SEDIMENTARY COMPONENTS ARE ALTERED OR OBLITERATED AND NEW COMPONENTS ADDED IN SUBSURFACE ENVIRONMENTAL REALMS

Processes	*Realms of Weathering*	*Realms of Diagenesis*	*Realm of Anamorphism*
KATAMORPHIC ALTERATION. Mineral changes through processes of carbonation (desilication), oxidation, hydration, *et cetera*	MAJ	MIN	
ANAMORPHIC ALTERATION. Simple recrystallization without mineral change		MIN	MAJ
ANAMORPHIC ALTERATION. Recrystallization with mineral change through processes of dehydration, silication, deoxidation		MIN	MAJ
SOLUTION. Partial or complete removal by being dissolved	MAJ	SEC	MIN
CHEMICAL PRECIPITATION. Deposition from solution in aqueous medium. Precipitation in optical continuity on grains or as discrete crystal entities	SEC	MAJ	MIN
METASOMATISM. Mineral change by chemical replacement by solutions	MIN	MAJ	SEC
MECHANICAL INTEGRATION. Compaction of particles, including welding under high pressure conditions	MIN	SEC	MAJ
DIASTROPHIC MECHANICAL DISINTEGRATION. Breakage by diastrophic stress beyond elastic limit; granulation, brecciation	MIN	SEC	MIN
GRADATIONAL MECHANICAL DISINTEGRATION. Breakage by gradational stresses resulting from action of wind, water, ice, insolation, and plants and animals	MAJ	SEC	

MAJ—Major importance. SEC—Secondary importance. MIN—Minor importance.

DIAGENESIS

The term *diagenesis* has been involved in a diversity of geologic usage. Twenhofel[48] includes under the term all modifications of sediments under conditions of temperature and pressure normal to the surface or outer portion of the crust, and under environmental conditions which do *not* result in weathering or

[48] W. H. Twenhofel, *Treatise on Sedimentation*, 2d ed. (1932), p. 108. The Williams and Wilkins Company, Baltimore, Md.

destructive changes. By stipulating "under normal conditions of temperature and pressure" he automatically excludes most changes occurring in the high temperature-pressure anamorphic realm, either under deep-seated conditions or in shallower zones by dynamic or contact metamorphism. By excluding "katamorphic changes having for their objective the disaggregation of the sedimentary materials," he rules out most of the changes occurring in the atmosphere and interstitially down to the water table, that is, changes occurring in the zone of aeration or Van Hise's Belt of Weathering.

The essence of diagenesis and the extent of its domain are subjects which demand geologic attention. It seems that diagenesis is not a process or resultant in itself but is rather an integration of processes (Table VIII) and resultants by which sedimentary rocks and their components become adapted for existence in and to changes of an *aqueous medium*, free or interstitial, under moderate conditions of temperature and pressure, and in an environmental setting in which anamorphic and katamorphic alterations play a minor or incipient rôle. Temperature-pressure conditions strongly influence diagenesis and vary from those obtaining at the surface to those which cause the gamut of anamorphic alterations to be set in operation. Inasmuch as diagenesis does not necessarily or in all cases include cementation and lithification, Van Hise's term *Belt of Cementation* is not strictly applicable to this realm. Lithification is just an episode which may or may not, but ordinarily does, occur as a result of the series of changes which constitute diagenesis.

As indicated by Table VIII, chemical precipitation and metasomatism or replacement are the major diagenetic processes; aqueous solutions are the dominant operative agents. There are three potential sources of the precipitated and replacing materials: (1) from the weathering realms by solution and removal, (2) from igneous emanations, and (3) from solution and removal within the diagenetic realm itself. Metasomatism commonly is selective in its attack and may allow replacement of certain constituents of a sediment without affecting the remainder. Aragonite, as a simple example, is much more prone to the influence of metasomatising solutions than is calcite. Of secondary importance in diagenesis are the processes of mechanical integration or compaction, diastrophic disintegration or breakage, and solution and removal. Katamorphic and anamorphic alteration processes are of minor importance.

Realms of diagnesis.—Diagensis does not function uniformly throughout its sphere of influence but rather shows some differentiation into realms, in which its processes operate with different degrees of rigor and thereby produce somewhat different effects. Diagenesis in the *surficial* or *hydrospheric realm* (I-B) is influenced by the free mobility of the aqueous medium and by transportation of sedimentary materials. Among the processes which may occur is metasomatism, including primary dolomitization, silicification, sideritization, and so forth.

Transitional or *near-surface diagenesis* (II-B) is poorly understood, but the few studies that have been made indicate that it is capable of producing marked

changes in the incorporated sediments. For example, Twenhofel's study[49] of the diagenetic changes occurring in the deposits of Lake Mendota near Madison, Wisconsin, have shown that there is a marked gradation within a 10-foot section of sediment, from a deep black soup-like mixture filled with carbonaceous matter on the lake bottom down to a white wet mud in which there is little carbonaceous matter 10 feet below bottom. It is suggested that microörganisms are responsible for this progressive downward dissipation of the organic materials. Many near-surface marine sediments are known to support a teeming population of microscopic and macroscopic organisms, and it is believed that most marine sediments of slow accumulation make many passages through intestinal tracts, these passages producing attritional effects, eliminating organic matter, and causing other chemical alterations. Fossil remains also may be nearly or completely destroyed by this action.

The transitional diagenetic realm is one of maximum change and adjustment to subsurface aqueous conditions. Materials most prone to redistribution are unstable minerals, dispersible colloids, and chemically reactive substances, and include colloidal silica, calcium phosphate, calcium carbonate, ferrous carbonate, iron disulphides, and several other compounds. In addition to organic processes, others are active, such as compaction, metasomatism, and incipient anamorphic alteration, the latter including the abundant development of fine white mica in some clays and shales soon after deposition. The results of some marine dredging have shown that in many cases lithification is accomplished in this transitional realm.

The *subsurface diagenetic realm* (III-B) differs from the transitional in that it lacks the ready interchange of interstitial solutions with surface waters and in that temperatures and pressures are slightly to considerably higher. Thus the processes differ in their competence; the activities of organisms practically cease, compaction becomes more effective, and stress conditions are initiated that may cause fracturing of certain of the components. Reducing conditions tend to prevail in this realm, especially if circulation is sluggish, and highly oxidized substances are likely to suffer a degree of reduction. Metasomatism may cause great changes, such as secondary dolomitization, phosphatization, and silicification of limestones. Some components may be dissolved and obliterated; others may undergo simple recrystallization; concretions may form. Many little understood alterations occur which deserve investigation, such as the formation of sedimentary feldspars, rutile, leucoxene, and glauconite. Thus many of the attribute parameters and properties of the primary sedimentary assemblage may be changed, textures and structures partially or completely destroyed and new ones instituted.

The British geologist Smithson[50] is pioneering in the study of the mineralogic

[49] W. H. Twenhofel, "The Physical and Chemical Characteristics of the Sediments of Lake Mendota, A Fresh Water Lake of Wisconsin," *Jour. Sed. Petrology*, Vol. 3, No. 2 (1933), pp. 68–76.

[50] F. Smithson, "The Alteration of Detrital Minerals in the Mesozoic Rocks of Yorkshire," *Geol. Mag.*, Vol. 77, No. 2 (1941), pp. 97–112.

and textural changes wrought by subsurface diagenesis, these changes being designated as "intrastratal changes" by some workers. Smithson's recent studies have shown that mineralogic variations within certain British strata, variations formerly thought to be due to initial distributive differences in sedimentation, are actually the result of differential post-depositional diagenetic action. He points out that there are three possible factors which may cause differences in the heavy-mineral assemblages in different localities: (1) the existence at the time of deposition of two or more contemporaneous distributive provinces, (2) differences in the age of the rocks, (3) areally differentiated mineralogic changes subsequent to deposition. The importance of the latter of these factors is coming to be more and more realized; failure to take it properly into consideration may lead the petrographer to erroneous conclusions, particularly on questions of provenance. Smithson has shown that mineralogic changes in Triassic and Jurassic rocks in Yorkshire have been particularly active in certain belts and have led to the general impoverishment of the detrital suite through the decomposition of garnet, staurolite, possibly monazite, and so forth. Outward from these belts the mineral assemblage tends to increase in richness. Other changes such as the regional development of authigenic brookite and of outgrowths on zircon also have occurred.

WEATHERING

Weathering and *diagenesis* are complementary. Taken together, they comprise the gamut of changes which rock materials suffer under the moderate, non-anamorphic temperature-pressure conditions of the outer portions of the lithosphere. Minerals formed under weathering and diagenetic conditions are in general few in number, chemically simple, and with low specific gravities.

Weathering, however, rather than denoting adaptation to totally aqueous conditions, stands for the sum total of processes and resultants by which rock components become adapted for existence in and to changes of an *aerial medium*, atmospheric or interstitial, under the influence of oxygenated and slightly acid meteoric (vadose) waters. All of the processes obtaining in the weathering realms occur also under diagenetic conditions; the relative importance of these processes, however, differs greatly in the two cases. Katamorphic alteration by carbonation (desilication) and oxidation is the dominant process under weathering conditions and of minor import below the water table in the diagenetic realms where these processes are limited, as a rule, by the small amounts of CO_2 and O_2 present. Removal by solution is important in the weathering realms and usually of secondary importance under diagenetic conditions where the complementary process of precipitation from solution dominates the scene. Gradational mechanical processes, such as spalling, exfoliation, splitting and abrasion, are important in the surficial environments of weathering. Plants and animals play a significant rôle in the chemical and mechanical changes; organic acids are generated and further the weathering processes.

Realms of weathering.—Weathering, like diagenesis, does not function uniformly but shows a vertical differentiation. *Surficial weathering* (I-A of Fig. 8) takes place under the full sweep of the atmospheric gradational agencies and is influenced by pronounced temperature changes and climatic vagaries. Surficial plants and animals play important direct and indirect rôles. The *transitional weathering realm* (II-A) is one of disaggregation, of maximum change and adjustment to surface climatic conditions; here the stage is set for reduction of the surface by erosion. That there is a differentiation of processes and products within this realm is indicated by the development of the soil profile, due partly to the selective redistribution of mineral and organic matter by vadose water migrating through the soil. The most potent climatic factor influencing transitional weathering is the amount of rainfall and the resulting moisture content of the soil. The *subsurface realm* (III-A), extending down to the water table, is for the most part protected from surficial climatic vagaries; thus the weathering processes differ in competence, and plant and animal activities are of little consequence.

REALM OF ANAMORPHISM

As indicated by Table VIII, this realm, with its dynamic, contact, and static phases, permits the functioning of several of the processes common to the realms of diagenesis and weathering but is differentiated by the dominance of anamorphic alteration, occurring as simple recrystallization without mineral change or as recrystallization with mineral change through the processes of silication, dehydration, deoxidation, and so forth. Environmental adaptation results in the production of pyroxenes, amphiboles, chlorite and micas, and other platy or columnar silicate minerals from the carbonates, hydrates, oxides and other components of sedimentary rocks. In this way dense crystalline slates, schists, and gneisses are formed and environmental equilibrium approached. The contact phase of anamorphism furnishes high temperature and pressure conditions for the acceleration of anamorphism in the more deep-seated regions and for introducing the anamorphic realm to regions nearer the earth's surface where diagenesis or weathering normally dominates the scene. Thus the anamorphic realm has no depth restriction.

In the high temperature-pressure environment of this realm, deformation is largely by chemical processes, in contrast to the dominantly mechanical deformation of the diagenetic and weathering realms; mechanical work nevertheless occurs, in the form of further compaction, welding, and granulation. Precipitation and cementation here are of far less consequence, and metasomatism occurs but differs in character from that of the other realms.

REALM OF FUSION

Once a sedimentary rock becomes fused, the resultant material is a magma, and the crystalline rock which forms by cooling has the characters of an igneous rock. Thus, sedimentary identity is partially or completely lost, depending on

how extensive the melting is, whether by such partial processes as *lit-par-lit* injection or by anatexis or complete regeneration (palingenesis). When this environmental stage is reached, the rock materials leave the sedimentary domain and thus are no longer pertinent to the subject of the present paper.

EPIGENETIC PROCESSES AND CHANGES AFFECTING CRINOIDAL SEDIMENT

Diagenesis.—The outstanding effect of diagenesis on the Grand Tower limestone crinoidal phase (Bed 9) has been cementation by epigenetic precipitation of calcite in the interstices between the crinoid plates and quartz grains (Pl. I). Lithification by this process may have been partially or completely accomplished soon after burial and in the early or transitional stage of diagenesis (Fig. 8).

The *MgO* content of the crinoidal limestone, treated in the section on chemical composition, is only 0.36 per cent, which is much lower than it should be judging from results of chemical analyses of modern crinoids. In a paper by Clarke and Wheeler[51] the *MgO* content of modern crinoids from various localities in the Atlantic and Pacific was described as being from 2.49 to 5.13 per cent, averaging approximately 4.25 per cent; the calcium carbonate of the plates was found to be in the form of the mineral calcite, not aragonite. Clarke and Wheeler also found from analyses of crinoids from Ordovician to Eocene in age that the remains of these fossil forms contained considerably less *MgO*, nine of the ten crinoids analyzed averaging only 0.75 per cent *MgO*. According to their reasoning, it is possible that the ancient crinoids may have been deficient in magnesia, but it is more probable that the loss is due to alteration during diagenesis, perhaps to the infiltration and precipitation of calcium carbonate in the somewhat porous crinoidal plates. This obviously would lower the apparent proportion of magnesia. Thus the magnesia deficiency in the composite analysis of the Grand Tower crinoidal limestone, compared with analyses of remains of modern crinoids, probably is due at least in part to diagenetic infiltration of calcite in the crinoid plates and to the presence of interstitial calcite cement and other minerals (mainly quartz), which reduce the relative proportion of *MgO* in the chemical analysis. Part of the magnesia deficiency may have been caused by solution and leaching during diagenesis, but calcium carbonate should then have been removed to a greater extent than magnesium carbonate.

Diagenesis has brought about a change in the mass texture of the crinoidal sediment from a fragmental-textured sand, at the time of deposition, to a crystalline-textured limestone. This change is due largely to interstitial precipitation of calcite, binding the aggregate so as to form a calcareous mosaic of crystals, each crinoid plate representing an individual calcite crystal.

The thin-section photomicrographs of Plate I show the crinoid plates to be irregularly fractured. It is probable that this is the result of diastrophic breakage,

[51] F. W. Clarke and W. C. Wheeler, "The Composition of Crinoid Skeletons," *U. S. Geol. Survey Prof. Paper 90-D* (1914), pp. 33-37.

occurring during diagenesis when the rock was subjected to stress conditions which attended faulting of the region. Intense faulting is known to have occurred in the Little Saline Creek area, in the vicinity of Ozora, soon after Middle Devonian time.

Weathering.—One notable effect of weathering on the illustrative crinoidal rock is the local katamorphic alteration of magnetite grains to limonite, producing slightly yellowish patches in the rock. Although it is possible that the limonite grains may have been deposited as such, it is more probable that they have been formed by epigenetic alteration (oxidation and hydration) of magnetite grains, some of which remain unaltered in the deposit; this alteration probably was accomplished by vadose waters in the belt of weathering.

Another probable effect of weathering on the crinoidal rock is the increase in porosity of the rock aggregate as a result of solution and removal of calcite locally along minute channel ways in the rock. As described under porosity, the crinoidal limestone in the section sampled has an average effective porosity of 7.2 per cent; much of this probably is due to solutional removal in the belt of weathering.

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GEOLOGICAL NOTES

TWO MORE ORDOVICIAN WELL-CORE GRAPTOLITES, CRANE COUNTY, TEXAS[1]

CHARLES E. DECKER[2]
Norman, Oklahoma

INTRODUCTION

Some time ago fragments of a core containing graptolites were sent the writer by M. E. Upson of the Gulf Oil Corporation, Fort Worth, Texas. The core is from McKnight No. 4, Crane County, Texas. A very delicate dendroid form of *Callograptus* came from a depth of 6,458 feet, and one side of an extensiform *Didymograptus* came from a zone 21 feet lower at 6,479 feet. This is the fourth well in Crane County from which the writer has secured graptolites. It is purposed here to describe and illustrate these two forms and suggest their significance for correlation.

The writer is indebted to the Gulf Oil Corporation of Forth Worth, Texas, for supplying the graptolites for study and for giving permission to publish information in regard to them. Also, acknowledgment is made to the Oklahoma University Research Committee for funds to pay part of the expense for preparation of this material for publication.

Besides the description and illustration of these forms, comparison is made with similar species elsewhere. As *Callograptus* is a dendroid form of a more primitive type, having its origin far down in the Cambrian, it is treated first, and the *Didymograptus*, belonging to the more recent Graptoloidea, is considered afterward.

DESCRIPTION OF SPECIES

Order DENDROIDEA Nicholson 1872

Genus CALLOGRAPTUS Hall 1865

Callograptus tenuissimus Decker n. sp.

Plate 1, Figures 1a–1d

The name *tenuissimus* is given to this new species because of the very extreme narrowness of the stipes, being narrower than those of any known *Callograptus*. While large parts of the colony can not be seen, enough has been preserved to show its beautifully symmetrical form, the very thin closely spaced branches with numerous bifurcations at irregular intervals, and its numerous closely crowded thecae. The general shape is infundibuliform, or funnel-shaped, as shown in the sketch drawing (Fig. 2) which illustrates how the two sides of the funnel have been crushed until they approach one another. Dissepiments are few

[1] Manuscript received, September 26, 1942.

[2] Professor of paleontology, University of Oklahoma.

and slender. The basal angle of the colony is about 100° to 110°. The bifurcation distance varies from 1 to 2.5 mm. After bifurcation the branches soon become subparallel. They are very narrow and 24 to 32 are crowded into the space of 10 mm., so that the interspaces are either less than, or about equal to, the width of the branches. Regular thecae are small and closely crowded, 32 to 50 in the space of 10 mm. Some elongate narrow bithecae occur nearly parallel with the edge of the branches, and other small ones occur at all angles on the surface, showing only under relatively high magnification. The width of the preserved part of the colony is 52 mm. and the height 30 mm., though the top is evidently truncated at the edge of the core. The branches vary in width from 0.125 to 0.25 mm.

Discussion.—This species is more delicate than any known American or British species, though it is most similar to the British *Callograptus tenuis* Bulman (1, p. 90, text Fig. 43, Pl. 10, Figs. 6–8)[3] though it has much narrower stipes and smaller more crowded thecae. It is much more delicate than the relatively common and widespread *Callograptus salteri* Hall (5, p. 135, Pl. 19, Figs. 4–6) from the Lower Ordovician of Canada, illustrated from the Deepkill of New York by Ruedemann (6, p. 584, Pl. 3, Figs. 13–15) and from the Arenig of Great Britain by Bulman (2, p. 81, text Figs. 39, 40, Pl. 9, Figs. 1–7). *Callograpti* were highly developed in the Upper Cambrian, but they became most abundant in the Lower Ordovician.

Correlation.—As this is a new species we can not assign to it a very specific value for correlation. However, in Great Britain it may occur in subzone (a) of the *Didymograptus extensus* zone, as Elles (3, p. 101) indicates that dendroid graptolites occur most abundantly in that subzone which is about the middle of the Skiddaw slates. Its nearest counterpart, *Callograptus tenuis* (2, p. 90) is from the Upper Arenig of Great Britain. This should represent a horizon in the lower part of the Deepkill of New York and considerably below the top of the Arbuckle group of Oklahoma. It comes from a zone 21 feet above the *Didymograptus* described in the following paragraphs.

Occurrence and type.—It occurs in a black argillaceous limestone 6,458 feet below the surface in the McKnight well No. 4, Crane County, Texas, and the holotype is in the Museum of Invertebrate Paleontology, University of Oklahoma No. A2040.

Order GRAPTOLOIDEA Lapworth 1875

Genus DIDYMOGRAPTUS McCoy 1851

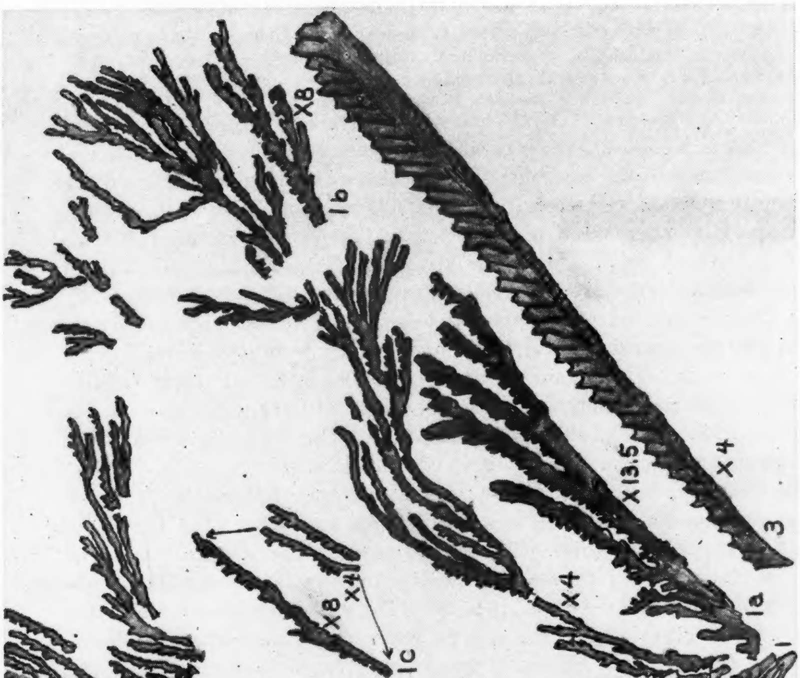
Didymograptus cf. *bartrumi* Benson and Keble

Plate 1, Figure 3

Didymograptus bartrumi Benson and Keble, 1935, *Trans. Roy. Soc. New Zealand*, Vol. 65, p. 281, Pl. 31, Fig. 19.

Original description.—Stipes diverge at an angle of 140° from a stout sicula 2.0 mm. or more in length and furnished with a nema. At their origin they are 0.8 mm. wide, but

[3] First figures in parentheses indicate references at end of text.



EXPLANATION OF PLATE 1

FIG. 1.—1a to 1d, *Callograptus tenuissimus* Decker n. sp. 1, side view of colony x4; 1a, enlargement of fragment with several branches x13.5; 1b, 1c, enlargement of fragments x8; 1d, x10 to show detail.

Fig. 2.—Sketch drawing to illustrate infundibuliform habit of species which is funnel-shaped.

FIG. 3.—*Didymograptus* cf. *bartrumi* Benson and Keble, x4 in side view. Showing thecae with large amount of overlap, coenosarcal canal along dorsal side with several round openings, or possibly muscular scars, and toward distal end short divisions which simulate thecae, but they may be only fractures.

expand to over 2.0 mm. at their distal ends. In length they reach 24 mm. or more. Thecae are from 13 to 15 in 10 mm.; relatively narrow tubes four or five times as long as wide and overlapping $\frac{2}{3}$ to $\frac{3}{4}$ of their length; ventral margins straight, inclination 45°; apertural margins straight or slightly concave and rather oblique.

Description of hypotype.—As only one stipe is present (the sicular region and the other stipe being absent) the general shape is not known, so this specimen is tentatively referred to the foregoing species. However, the specimen from the Crane County well tallies closely with the characteristics of a stipe of *D. bartrumi* in size, shape, in number and shape of thecae, and in the angle of inclination. This angle of inclination is 45°. The thecae are simple tubes with slightly curved apertures, and they occur 14 in 10 mm. A coenosarcal canal shows clearly along the dorsal margin, and in it there appear to be small circular openings which may represent apertures, possibly of bithecae, or they may be muscle scars. Toward the distal end of the stipe the canal seems to be divided into small, short, cell-like structures which may be only fractures. The length of the stipe is 27 mm. The width varies from 0.87 to a little more than 2 mm. The thecae have a width of about 0.5 mm. and a length of 2 mm. in the distal region.

Discussion.—While this species approaches the form of *D. nitidus* (4, p. 10, Pl. 1,Figs. 2a–c; p. 569, Pl. 1, Figs. 1–9; 7, p. 611, Pls. 13, Figs. 1–5; 14, Figs. 5, 6), it is much more like *D. bartrumi* in number and size of thecae, width of stipes, and angle of inclination. This form has great rigidity and retains its shape, as do most *Didymograpti*. Rigidity is developed in forms of this genus in spite of the fact that they lack a strengthening rod, the virgula, which is so characteristic of *Monograptids* and *Diplograptids*. Instead of developing a regular virgula, these forms may acquire rigidity by a general thickening of the dorsal and side walls of the coenosarcal canal.

Correlation.—In the Lower Ordovician of New Zealand, *Didymograptus bartrumi* is associated with *Tetragraptus fruiticosus* which is associated with *T. serra*. *T. fruiticosus* occurs in the Middle Bendigo of Australia (6, pp. 52, 53), in the Lower Ordovician of Canada (5, p. 91), and in the lower Deepkill (7, p. 651) of New York. In the Lower Ordovician Skiddaw slates of Great Britain (3, p. 101), *T. serra* occurs in the main *Didymograptus extensus* zone and in the *Tetragraptus* and *D. deflexus* subzones. These zones in which *T. serra* occurs are a little below the *Didymograptus nitidus* zone in which *D. protobificus* is found in abundance. Accordingly, this should place *T. serra*, *T. fruiticosus* and *D. bartrumi* a little below the *D. protobibidus* zone in Oklahoma. In the Arbuckle Mountains this zone is a little more than 800 feet below the top of the West Spring Creek, the uppermost formation in the Arbuckle group. In Texas this graptolite zone should be in the Lower Ordovician part of the Ellenburger formation.

Occurrence and type.—This *Didymograptus* occurs 6,479 feet below the surface in the McKnight well No. 4 in Crane County, Texas. This is 21 feet below the *Callograptus* described in the preceding paragraphs. The hypotype is in the Museum of Invertebrate Paleontology, University of Oklahoma, No. A2041.

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7. RUEDEMANN, RUDOLF, "Graptolites of New York," Pt. 1, *New York State Mus. Mem. 7* (1924), pp. 649–52, 671–74.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
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DISCUSSION

STRATIGRAPHY OF NORTH DAKOTA[1]

NORVAL BALLARD[2]
Oklahoma City, Oklahoma

Since Dr. Kline's article entitled "Stratigraphy of North Dakota"[3] appeared in the *Bulletin*, additional information has been made available by the drilling of the Carter Oil Company's Semling No. 1, Sec. 18, T. 141 N., R. 81 W., Oliver County, North Dakota. Samples from this well to a depth of 6,600 feet have been made available to all interested companies.

After examining cuttings on the Carter test and those from the Prairie Oil and Gas Company's Armstrong No. 1 (Steele of Dr. Kline), the writer finds there is a wide disagreement with Dr. Kline's correlation of the driller's log. Dr. Kline assigns beds from 2,535 to 2,989 feet to the Devonian system. The writer agrees with Seager that beds from 2,515 to 2,770 containing red or green sandy shales with 4 or 5 feet of cherty limestone pebble conglomerate at the base should be included in the Jurassic since other tests show that beds of that age overlap strata as old as Devonian in an easterly direction. Seager, in discussing Dr. Kline's paper, suggests that part of the redbed section from 2,770 to 2,990 may be Triassic in age. It is also possible that these beds of limestone, anhydrite, and red shale may be some representative of either Permian or Pennsylvanian age. The beds between 2,988 and 3,490 probably belong to the Big Snowy group, upper and middle Mississippian. Samples from 3,490 to 3,884, total depth, were not available to the writer but they have been examined by Dr. Waldschmidt, Colorado School of Mines. He logs these beds as gray to white limy powder similar to cuttings from 3,400 to 3,490 feet. Correlations between the Semling No. 1 and the Steele test suggest that the latter may have reached the top of the Pahasapa between 3,525 and 3,575 feet. It is probable that the Steele test was bottomed in Mississippian limestone instead of Cambrian as Dr. Kline suggests.

[1] Manuscript received, September 12, 1942.

[2] Consulting geologist.

[3] Virginia Kline, "Stratigraphy of North Dakota," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 26, No. 3 (March, 1942), pp. 336–79.

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REVIEWS AND NEW PUBLICATIONS

* Subjects indicated by asterisk are in the Association library, and available, for loan, to members and associates.

OIL WELL DRAINAGE, BY STANLEY C. HEROLD

REVIEW BY W. S. W. KEW[1]
Los Angeles, California

Oil Well Drainage, by Stanley C. Herold. 399 pp. Stanford University Press, Stanford University, California (1941). Price, $5.00.

This is a book which tells in simple language the story of oil-well drainage. It is in marked contrast to Dr. Herold's earlier (1928) book on *Analytical Principles of the Production of Oil, Gas, and Water from Wells*, in which mathematical equations are used without stint. In contrast, the present work is easy reading and the author's thoughts should be clearly understood by the layman. The geologist will be interested in the book, since Dr. Herold shows the important and essential rôle which geology plays in the principles of oil production. In fact, geology is shown to be so closely related that it is unwise to attempt to solve many engineering problems without a geological background. It must be conceded by both geologists and petroleum engineers that the character of the reservoir rock is fundamental in the study of the production of oil, gas, and water. Thus it is a welcome note to have this book prefaced by a tribute to Dr. James Perrin Smith, who, as professor of paleontology at Stanford University, undoubtedly influenced the author in his leaning toward the importance of geology.

A striking and unusual feature of this book is the dual treatment of the subject in each of the chapters which discuss the characteristics and functions of reservoirs. Two types of reservoirs have been designated: one as "Cenozoic" and the other as "Paleozoic," the distinction being based mainly "upon the behavior of the intimate mixture of oil and gas within the pool." In general, the author says the younger, or Tertiary, pools belong to the Cenozoic class, wherein the oil and gas is not locked in place within a granular medium. In the Paleozoic type of reservoir, he continues, water drive is absent and the oil and gas are locked in place; these reservoirs are said to be represented largely by the Mid-Continent and eastern fields. The author does not compromise but states that production from a well at any particular time comes from either the Cenozoic or Paleozoic type of reservoir. To many readers it may seem that the choice of these geologic time-scale terms is unfortunate because they are not descriptive of the type of reservoir except possibly as to their geologic age. The usage of these terms, so well known to geologists, is so unfamiliar that it may take time for them to become commonplace.

Chapters one and two are particularly important, because they describe in simple language the Cenozoic and Paleozoic types of reservoir. The influence of gas pressure, and later that of water, is shown for the first type. For the Paleozoic type the relation of the Jamin capillary tube and its effect on this type of reservoir is explained.

The conditions under which natural oil reservoirs are found are presented concisely and clearly in chapter three. Sedimentation, formation of structures, and the accumulation of oil, with a description of the various types of traps, give the reader a relatively simple picture of subsurface conditions. An exception might be taken to the author's statements that pools shift position with minor folding and tilting. However, one can not disagree

[1] District geologist, Standard Oil Company of California. Manuscript received, October 5, 1942.

with his statement on structure as it relates to the accumulation of oil, that "Deposits of oil and gas appear to have been influenced somewhat by chance, or, as we say, by the accident of nature." Experienced petroleum geologists well know this to be true. Many instances can be cited where fields have been discovered where the structure and lithology proved to be quite different from the structure and lithology originally outlined by the geologist prior to drilling. This all leads to the author's conclusion that to discover oil one has to take big chances. These chances are considerably reduced if two fundamental conditions are present; that is, if the formation is favorable for containing oil, and a structure is present to trap it.

With a geologic background of the occurrence of oil the subjects more closely concerned with engineering are taken up: namely, reservoir energy and function of gas in the production of oil.

Drainage of pools is the subject of a long discussion in three chapters titled "Radius and Area of Drainage," "Regional Drainage and Water Encroachment," and "Drainage across Property Lines." The author considers many conditions and illustrates his points by simple comparisons. His direct statements with simple explanations bring the meat of the subject clearly to the reader.

Chapter nine, under the heading "Effects of Stratigraphy and Structure," points out the necessity of using all types of scientific evidence for the determination of stratigraphy and structure. Many are inclined to use the tool with which they are most familiar, to the exclusion of others. This prejudice may easily, and often does, lead a geologist or engineer astray, with needless expenditure of money. Geological conditions are commonly not clear, even with good surface exposures, so it is to be expected that structure, at depth, will be even more difficult to decipher. This discussion leads to the vagaries of the accumulation of oil and the description of the numerous types of traps with reference to the paths of migration of oil and the reasons why certain pools occur. Folding and faulting subsequent to the accumulation of oil are stressed. Faulting in California fields after or during oil accumulation is certainly to be recognized as a very important factor in the localization of oil. Contrary to his statement that faults in the Inglewood field, California, do not affect production, it is generally recognized that faulting here is of importance in this respect. The discussion in part two of this chapter, concerning the prime forces in the earth which cause structures, might have been placed to better advantage in the first part, which describes the details of structure. As a whole, this chapter is important, in that the relationship between oil accumulation and lithology and structure is explained. The idiosyncrasies of oil accumulation are the rule, and every geologist and engineer must keep an open mind on this subject.

Chapter ten, dealing with the effects of reservoir penetration on drainage, links the engineering problem with geological conditions, especially sedimentation and its heterogeneity. These variations in arrangement of mineral grains and thickness of strata influence rates of production, drainage, and edge-water encroachment. However, when dealing with these varied sand conditions the author emphasizes the fact that true correlations can best be made by the use of shale strata, which generally have a more uniform extent.

Chapters ten to seventeen, inclusive, deal with various problems of the production of oil and gas. These chapters are of interest to geologists as well as engineers, for they contain good common sense practice. Furthermore, the author's ideas are tied in with geology, which is essential but not always made use of by engineers who discuss these subjects.

Chapter eighteen, on curtailment, proration, and conservation, is in reality an essay emphasizing these subjects as matters of economics, and it is stated that these are not technological problems. The rôle of economics is concerned with the ultimate production from a property which can be adequately drained by the least number of wells and efficient spacing. These problems, of course, differ for Cenozoic and Paleozoic production, the latter

being helped by secondary recovery methods, with the prospect of leaving less undrained oil in the ground. In the matter of conservation, the author holds somewhat unusual views. He believes some good may result from unit operations and equitable proration, but this pertains only to the economics of production and does not concern the technology of production.

It is a book well and sanely written and contains many sensible suggestions. Contrary to his earlier work, this is not too technical for the average geological student who has not delved deeply into mathematics and physics. For all types of student there are many suggestions for good oil-field practice. The author's own statement from his last chapter is apropos here to summarize the thesis of this book: "We have the evidence here that drainage is a complex subject which involves not only the principles of theoretical mechanics, but also the principles of sedimentary geology. It would be wrong to believe that our knowledge of these principles today is all that can be necessary for the practical purposes of producing oil and gas. Every well, and every field, will always be found to have individual characteristics. The general solution of problems may be known fairly well at the present time, but the specific solution of the smaller problems is that which may easily swing the balance in the ledger from one side to the other. This is our consideration for the days to come."

OIL PROPERTY VALUATION, BY PAUL PAINE

REVIEW BY ERNEST K. PARKS[1]
Los Angeles, California

Oil Property Valuation, by Paul Paine. 203 pp. John Wiley and Sons, Inc., New York, N. Y. (1942). Price, $2.75.

Paul Paine has written a comprehensive book. It is informative, critical and constructive. He writes a plain language which can be understood by anyone. "The way of an appraiser," he says, "is not easy, even when luck is with him." This confession does not appear at once but the reader will soon appreciate that "oil property valuation" is an art applied in a business which is "saturated with bewildering incongruities." Nevertheless, the author details the fundamentals of the problem: its analysis, the technique of solution, and the reporting of results, all with a wholesome simplicity that makes his text a biography of experience invaluable to those who have anything to do with the subject whether they be advanced students, professional engineers, attorneys, bankers, investors, or businessmen.

Paine writes from no biased standpoint. He values old customs but points out new conditions, he uses technology but warns of its limitations, he appreciates good accounting but realizes danger in figures. He favors neither the operator nor the land owner, and as for the law, he is no reformer but believes in dealing with men and things as they are.

One will soon see that Paine has the viewpoint of the professional engineer: a keen sense of personal responsibility and a relentless search for the truth. He has no patience with devices for imparting an "aura of precision over the reckoning."

"Valuation," says Paine, "is never an end in itself, but may be required for any one of many purposes." This statement indicates at once that Paine has no fear of the controversial subject. His middle ground is confined to judgment, not to principles.

The book properly begins with a chapter on the "Scope of Valuation": its meaning, purpose, general methods of determination, and the relation of the appraiser to his employer. This chapter will clearly acquaint the reader with the author's point of view. He

[1] Petroleum production engineer, 614 South Hope Street. Manuscript received, September 23, 1942.

believes that the "client should be handed the facts." He has no patience with "conservatism," especially when this causes the appraiser to employ "artificial hedges as 'factors of safety'." Paine advocates "unmistakable clarity" in reports to clients and says that the appraiser should show "what deep down in his heart he generally considers to be the correct estimate or answer."

With this clearly established position, Paine proceeds at once to the details, the first of which is a description of all sorts of oil properties and oil property interests. Those whose experience has been confined to one locality, or class of valuation, will find a surprisingly large number of variations in forms of ownership. Paine gets down to cases, gives definitions, examples, and contributes lists of required data and a useful table giving the products of customary fractions used in dividing oil-property interests. The author thus proceeds to make his book a useful guide for the experienced engineer and valuable instruction for others.

The subject of "Unproved Lands" is skillfully treated. Despite the fact that "no satisfactory workable formulas have been developed," the author describes certain measures of value which are discussed in a most helpful manner. He particularly condemns "the placing in oil reserves [of] an estimated amount of oil which it is expected will be obtained from the 'proved or semi-proved' acreage" and advises, rather, to use "something corresponding to market value" as an index for appraisal purposes.

The next and last four chapters entitled "Oil and Gas Reserves," "Elements in Valuation," "Valuation Methods," and "The Examination and Report" set forth the working details of oil-property valuation. The author, however, treats these matters in a non-technical style and brightens the pages with historical incidents, unexpected asides and philosophical paragraphs which reveal his broad experience with oil-producing enterprise in its technical, operating, business, and legal phases.

The chapter on "Oil and Gas Reserves" contains much that is already familiar to engineers, but Paine defines the terms, describes the methods, and discusses the results in an effort to describe the important features of oil and gas reserves for the benefit of those who are not immediately concerned with technology. The technician will find fault with omission of details and with generalized statements, especially when he encounters Paine's description of retrograde condensation, to which only one paragraph is devoted. This chapter, however, is not for those who are expert but is designed to be especially useful to clients of professional engineers, to attorneys, and others who wish to know in general something of the basis of the estimate.

The chapter contains excellent examples of cases when the unexpected happened, illustrating the author's obvious contention that meticulousness of calculation is no substitute for judgment because "the valuation of oil wells remains an uncertain and difficult undertaking."

"Elements in Valuation" receives a thorough treatment. This chapter is comprehensive and valuable, especially an excellent compilation of ranges of well costs in fields of the principal oil-producing states, numerous cost ranges of particular operations, a hitherto unpublished summary of taxes levied against oil and gas produced in various states, state income-tax rates, and a record of past federal corporation income-tax rates. Present worth, of course, is included in this chapter with simple tables and graphic charts for usual values. The author might well have omitted these tables and charts, the fundamentals of which should be known to any qualified engineer or student, but it is inevitable that valuation books should repeat discount mathematics. The author holds that discount factors "should not be applied to oil reserves or its estimates of oil recovery." He limits the proper use of discount to hire of money, and says that "uncertainties are too great to permit their being pegged and disposed of with a mathematical factor."

In "Valuation Methods" the classic "engineering method" is explained in detail with excellent examples of data compilations followed by an interesting graphic record shown

to illustrate the "deviations of results from estimates" with respect to actual performance of a selected producing property. Other methods which are described are those based on the time to pay out, the average daily barrels of oil production, the well itself, and the barrels in the ground. Notwithstanding the unscientific nature of these methods, they are shown to be in common use as approximate measures of value. The most interesting part of the chapter is that devoted to remarks on valuations compiled for the lender of money, on royalties, and notably the discussion on fair market value about which it would be profitable for any petroleum engineer or oil property owner to read.

The last chapter on "The Examination and Report" gives practical directions on how to go about a job, the examination of accounts, and the preparation of a report, with a thorough check list of items to be included. There is advice on court appearances and on special reports which may be required for the Securities and Exchange Commission and for various regulatory bodies. There is a unique compilation of the requirements of various state securities commissions.

The book is printed with convenient subtitles and paragraph headings. There are 26 graphs devoted to the illustration of production data, but except for a few standard examples of curve plotting on several types of coördinates, the charts are unusual in that they depict the actual results of the unexpected. Violent changes are shown to have occurred from many causes, and this assembly of discontinuity in performance is most impressive.

There is a copious index and altogether the book of 203 pages constitutes a work which is an outstanding contribution to the art of oil-property valuation.

RECENT PUBLICATIONS

ARIZONA

*"Paleozoic Paleogeography of Arizona," by Alexander Stoyanow. *Bull. Geol. Soc. America*, Vol. 53, No. 9 (New York, September 1, 1942), pp. 1255–82; 5 pls., 3 figs.

ARKANSAS

*"An Engineering Study of the Magnolia Field in Arkansas," by H. F. Winham. *Petrol. Tech.* (New York, September, 1942). 20 pp., 6 figs. *A.I.M.E. Tech. Paper 1491.*

CALIFORNIA

*"Flood Deposits of Arroyo Seco, Los Angeles County, California," by W. C. Krumbein. *Bull. Geol. Soc. America*, Vol. 53, No. 9 (New York, September 1, 1942), pp. 1355–1402; 7 pls., 19 figs.

GENERAL

**Proceedings of the Eighth American Scientific Congress*, Volume IV. May, 1940, Congress, devoted to Geological Sciences. Dept. of State (Washington, D. C., 1942). 764 pp.

*"National Research Council and Co-operation in Geological Research," by Walter H. Bucher. *Bull. Geol. Soc. America*, Vol. 53, No. 9 (New York, September 1, 1942), pp. 1331–54.

KANSAS

*"Mineral Resources of Phillips County," by Kenneth K. Landes and Raymond P. Keroher. *Kansas Geol. Survey Bull. 41* (Lawrence, August, 1942), pp. 277–312; 4 pls., 5 figs.

KENTUCKY AND WEST VIRGINIA

*" 'Corniferous' in Eastern Kentucky and Western West Virginia," by R. C. Lafferty and Ralph N. Thomas. *Producers Monthly* (August, 1942). 10 pp., 6 figs.

TRINIDAD

*"Gamma-Ray Well-Logging in Trinidad," by Glenn M. Conklin. *Jour. Inst. Petrol.*, Vol. 28, No. 223 (London, July, 1942), pp. 141–45; 2 tables.

VIRGINIA

"Geology of the Appalachian Valley in Virginia," by Charles Butts. *Virginia Geol. Survey Bull. 52* (Charlottesville, July 1, 1942). Pt. I, "Geologic Text and Illustrations," 568 pp., 63 pls., 10 figs. Pt. II, "Fossil Plates and Explanations," 72 pls. of Paleozoic fossils (1,959 figures from original photographs and 592 named species). Price: Pts. I and II, $1.50; Pt. I not sold separately; Pt. II, $0.50.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 26, NO. 11 (NOVEMBER, 1942), PP. 1783-1786

THE ASSOCIATION ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The executive committee has approved for publication the names of the following candidates for membership in the Association. This does not constitute an election but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it promptly to the Executive Committee, Box 979, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each nominee.)

FOR ACTIVE MEMBERSHIP

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Edward D. Pressler, Ira H. Stein, Frith C. Owens
Jack B. Ferguson, Houston, Tex.
Dart Wantland, W. A. Waldschmidt, F. M. Van Tuyl
John Paul Gries, Rapid City, S. Dak.
Edward L. Tullis, M. M. Leighton, L. E. Workman
Leonard Latch, Lubbock, Tex.
David M. Evans, Raymond Sidwell, Leroy T. Patton
Leslie Walter LeRoy, Golden, Colo.
J. Harlan Johnson, F. M. Van Tuyl, W. A. Waldschmidt
William Willard Moore, Jr., Bogota, Colombia, S. A.
W. C. Hatfield, John O. Bower, Donald McArthur
Thomas Alonzo Ogg, Jr., Houston, Tex.
Leslie Bowling, J. Brian Eby, Hershal C. Ferguson
Elwyn Ronald Owen, Shawnee, Okla.
Roy P. Lehman, H. W. O'Keeffe, Charles R. Hoyle
Eduardo Simian G., Santiago, Chile, S.A.
Phil K. Cochran, E. B. Hutson, William S. Hoffmeister
Joshua Lawrence Soske, Pasadena, Calif.
F. M. Van Tuyl, C. A. Heiland, J. Harlan Johnson
Michael Wladimir Zaikowsky, Caracas, Venezuela, S. A.
Frank B. Notestein, John A. Poulin, J. M. Hamill

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J. Harlan Johnson, F. M. Van Tuyl, W. A. Waldschmidt
Hamdi Ahmet Bozbag, Golden, Colo.
F. M. Van Tuyl, W. A. Waldschmidt, J. Harlan Johnson
Ch'eng Yi Fu, Pasadena, Calif.
W. A. Waldschmidt, Ben H. Parker, F. M. Van Tuyl
Raymond Francis Keller, Houston, Tex.
Harry H. Sisson, G. W. Carr, Chester Sappington
Percy Marvin Lyons, Baton Rouge, La.
Henry V. Howe, J. Huner, Jr., Chalmer J. Roy

(Continued on page 1786)

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	John W. Inkster	

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

(*Continued from page 1783*)

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Ada Swineford, Lawrence, Kans.
Wallace Lee, Raymond C. Moore, L. R. Laudon

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AT HOME AND ABROAD

CURRENT NEWS AND PERSONAL ITEMS OF THE PROFESSION

Captain MICHEL T. HALBOUTY is an instructor in the Academic Department, Infantry School, at Fort Benning, Georgia.

BYRON RIFE, a lieutenant colonel in the Ordnance Department, has been transferred to the Office of the Field Director of Ammunition Plants, St. Louis, Missouri, and may be addressed at 4402 McPherson Avenue.

M. L. THOMPSON, formerly with the New Mexico School of Mines at Socorro, is now connected with the Department of Geology at the University of Kansas, Lawrence.

Ensign CARL B. IRWIN, U.S.N.R., has been transferred from Houston to Port Arthur Texas, for duties under the Petroleum Division, Bureau of Ships.

W. DOW HAMM is now chief geologist for Atlantic Refining Company (Domestic Operations), Magnolia Building, Dallas, Texas. He was formerly assistant manager of exploration for Shell Oil Company.

GLENN DEWAYNE HAWKINS, consulting geologist of Tulsa, Oklahoma, is a lieutenant (d.v.p.) in the Navy.

H. C. DAVIS has changed his address from Puerto Cabezas, Nicaragua, to 504 East Monroe, Austin, Texas.

WALLACE W. HAGAN, formerly a consultant in Urbana, Illinois, is now employed by the Indiana Department of Conservation, Division of Geology, Indianapolis, Indiana.

POWELL W. MILLER has enlisted in the C.P.T., Hobbs, New Mexico, and is receiving training as an army glider pilot.

U. R. LAVES, with the Office of Price Administration, has been transferred from Washington, D. C., to the Dallas, Texas, regional office. His title is machinery section head.

JOSIAH TAYLOR is connected with The Department of Terrestrial Magnetism, 5241 Broad Branch Road, N. W., Washington, D. C.

OSCAR R. CHAMPION has changed his company address from Amerada Petroleum Corporation to Seaboard Oil Company, Box 152, Midland, Texas.

GERSON H. BRODIE may be addressed at 173 Riverside Drive, New York City. He is working out of Bath, Maine, for the U. S. Geological Survey.

EUGENE C. REED is assistant State geologist and associate chief of the Conservation and Survey Division, University of Nebraska, Lincoln, Nebraska.

JOHN HOWARD SAMUELL has received a commission as captain in the Corps of Engineers and is located at the Pecos, Texas, Basic Army Air Force Flying School.

CARLETON D. SPEED, JR., may be addressed at the Park Central Hotel Apartments 1900 F Street, N.W., Washington, D. C.

E. B. DANA is geologist and field engineer for the North Basin Pools Engineering Committee, and may be addressed at Box 66, Sundown, Texas.

WATSON H. MONROE, U. S. Geological Survey, will be stationed at 304 North Lamar Street, Oxford, Mississippi, during the winter months.

JUAN J. ZUNINO has changed his address to Servicio de Exploracion de Y.P.F., Vespucio, Provincia de Salta, Republica Argentina, S. A.

VINTON A. BRAY was transferred several months ago from the Colombian Petroleum Company, Cucuta, Colombia, to the Texas Company (Venezuela), Ltd., Apartado 267, Caracas, Venezuela.

FRANK M. POOL, 1st lieutenant, is with the A.E.F. in the British Isles.

Lieutenant NOLAN A. FANGUY, an aviation cadet in the Army Air Corps, was killed in an airplane accident on August 22 at Meridian, Mississippi.

EDWIN A. MCKANNA died at his residence in Pasadena, California, October 9.

JOHN H. LOCK, 210 Farragut, Laredo, Texas, is now a marine stationed in San Diego, California.

It was erroneously stated in the September *Bulletin* that O. F. VAN BEVEREN had returned to this country. He is still with the California Arabian Standard Oil Company at Bahrein Island, Persian Gulf.

WILBURN H. SEALS, formerly of New Orleans, Louisiana, is a lieutenant (j.g.) in the U. S. Naval Reserve.

Officers elected at the first 1942–43 meeting of the Shreveport Geological Society were: president, G. D. THOMAS, Shell Oil Company, Inc.; vice-president, R. M. WILSON, The Ohio Oil Company; secretary-treasurer, T. H. PHILPOTT, Carter Oil Company, all of Shreveport, Louisiana.

HERBERT V. LEE is a lieutenant in the army, stationed at the Roney Plaza Hotel, Miami Beach, Florida.

ANNE M. ROBINS has changed her address from Center Conway, New Hampshire, to Box 336, Pauls Valley, Oklahoma, where she is computer on a reflection-seismograph field crew for General Geophysical Company.

J. B. SELOVER has been commissioned a lieutenant in the U. S. Naval Reserve. His mailing address is 10207 Lakeshore Boulevard, Cleveland, Ohio.

Newly elected officers of the Houston Geological Society are as follows: president, DONALD M. DAVIS, Pure Oil Company; vice-president, CARL B. RICHARDSON, Barnsdall Oil Company; secretary, WILLIAM L. HORNER, 2401 San Felipe Road; treasurer, WILLIAM F. CALOHAN, British American Oil Producing Company.

CECIL V. HAGEN, lieutenant (j.g.) in the U. S. Naval Reserve, has moved from Houston, Texas, to 633 N. Nelson Street, Arlington, Virginia.

OSCAR M. HUDSON has been transferred to the Evansville office of the Midstates Oil Corporation, 503 Court Building, Evansville, Indiana, where he is district geologist.

R. H. ROBIE, 3909 Huntington Street, N.W., Washington, D. C., is an ensign in the U. S. Navy.

The business office of the Society of Exploration Geophysicists has been transferred to Washington, D. C. Correspondence may be addressed in care of J. F. Gallie, P. O. Box 1925.

The Mississippi Geological Society has elected officers for the year, as follows: president, David C. Harrell, Carter Oil Company; vice-president, L. R. McFarland, Magnolia Petroleum Company; secretary-treasurer, K. K. Spooner, The Atlantic Refining Company, all of Jackson.

Douglas A. Greig, recently chief geologist for the Anglo-American Oil Company in England, has temporarily been transferred from geological work, and may be addressed in care of the Office of the British Petroleum Representative, Materials Division, 15 Broad Street, New York, N. Y.

George Taylor McIntyre, formerly with the geological department of the Cities Service Oil Company at Oklahoma City, Oklahoma, is a lieutenant (j.g.) in the U. S. Naval Reserve, in training at Harvard University.

A group of Colombian engineers and geologists founded in Bogota, December, 1941, the Colombian Institute of Petroleum, whose purposes are the study and better knowledge of the petroleum industry and all of its branches. Felix Mendonza is president.

Harold F. Pierce, 1304 South Indianapolis, Tulsa, Oklahoma, has entered the Coast Guard at New London, Connecticut, as a cadet.

W. L. Graham is now in the employ of the Mid-Continent Petroleum Corporation geological department, at Tulsa, Oklahoma.

At the October 5 meeting of the Tulsa Geological Society the program topic was "Our Place in the War," a review of work that can be and is being done by geologists and geophysicists. Speakers were A. R. Denison and W. T. Born. At the October 19 meeting Harry F. Wright spoke on "Valuation of Oil Reserves."

Following complete understanding and agreement with the Geological Survey of Canada, the 1942 annual meeting of The Geological Society of America, scheduled to be held at Ottawa, Canada, has been cancelled. It will be held on December 29 at the Headquarters of the Society in New York City; and, from a desire to coöperate with the Federal Government in reducing civilian travel and to encourage full concentration on war effort, the meeting will be limited to the usual business sessions.

Raymond C. Moore, State geologist of Kansas, was called into service on October 23. He reported to Cincinnati, Ohio, as a captain in the Engineer Corps as a specialist.

Norman D. Newell, former editor of the *Journal of Paleontology*, and a member of the geology faculty at the University of Wisconsin, Madison, is on leave of absence for employment by the Government of Peru, to make a general stratigraphic survey of the Government petroleum holdings in the foothills and jungle lands of eastern Peru. His address is in care of the Director of Petroleum and Mines, Ministerio de Fomento, Lima.

NOTES ON SELECTIVE SERVICE

A. R. DENISON[1]
Tulsa, Oklahoma

The National Selective Service Act is of vital importance to each of our members. It has as its function the "selection" of men to be placed in the several classes. To the

[1] Vice-chairman, National Service Committee.

majority of us it may appear that draft boards are for the sole purpose of "putting men in the army"; however, an equally important function is the selection of those who should remain in civilian life, by reasons of dependency or need in the civilian tasks of supplying the armed forces and maintaining the civilian economy.

Those who were between the ages of 20 and 45 when they registered will eventually be placed in one of the two groups—(1) those needed in the combat forces; (2) those needed in civilian life. The majority of our members are between these ages and therefore are directly affected by the functioning of selective service. Many members above the age of 45 have sons who have reached or will soon come of the age to be under selective service. It is, then, highly desirable that all members become familiar with and keep posted on the functioning of National, State and Local Selective Service. This can be done by following in newspapers, magazines, etc., the authentic information releases from National and State Headquarters. They can also learn how the selection of men for combat and civil life is functioning by consultation with their local draft boards.

For the purpose of advising local and state draft boards of the needs for men of technical training and skill in civilian life certain memoranda and bulletins have been issued by National Selective Service Headquarters. Those having the most direct bearing on our members (issued prior to October 1) are as follows:

1. Memorandum No. I-405 (Local Board Release No. 115)
   Subject: Occupational Classifications
   Date: March 12, 1942
2. Occupational Bulletin No. 10
   Subject: Scientific and Specialized Personnel
   Date: June 18, 1942
3. Occupational Bulletin No. 15 (Published in September 1942 Bulletin)
   Subject: Petroleum, Natural Gas and Natural Gasoline Activity
   Date: August 5, 1942

Memo. No. I-405—A basic manual which defines "Critical Occupations" and "Necessary Men"

Bulletin No. 10—Prepared from study made by National Roster of Scientific and Specialized Personnel. It lists scientific and technical skills necessary in war effort in which there are *shortages*. This list includes geophysicists but not geologists or petroleum engineers.

Bulletin No. 15—Prepared by *War Manpower Commission*, gives list of all occupations requiring more than six months' training which are critical to the oil industry. It does *not* say that there are *shortages* in these grades of men. The list includes:

Geophysical analyst
Engineer—professional and technical
Geologist
Geophysicist
Geophysical interpreter
Party chief—Geophysical
Physicist
Seismologist

These releases are on file with all local draft boards and copies may be secured from them or from State Selective Service Headquarters.

The bulletins mentioned and described above are called "directives," and do not have the force of "orders." They are issued by the National Headquarters of Selective Service for the purpose of giving State and Local boards information on which to base the proper classification of their registrants. The application of these directives, however, varies

according to the make-up and personnel of the local draft boards and are tempered by the conditions present in each local draft district. In other words the local draft boards are not required to follow to the "letter" of these directives but can apply them as they feel will best suit the needs of their community and the war effort. Such a diverse application will certainly lead to great discrepancies between the attitude of local boards. Even within the same town or county it may be found that there is considerable difference between the manner of classification of those employed in the identical occupations and with identical dependents.

In anticipation of such a variable interpretation, means have been set up whereby appeals can be taken from the classification of local boards. Each local board has an "appeal agent" to whom a board may turn when a protest has been entered regarding classification. Furthermore, each state has within its boundaries one or more District Appeal Boards whose function it is to hear and review protests made as to classifications by the local boards. The decision of this district appeal board is final unless the classification involves a question of dependency, in which case it can be carried through the State Board to the President as final authority.

As indicated above, appeals can be taken from the classification by local boards either on the grounds of dependency or due to the vital and necessary character of the registrant's work. In July of 1942 a new class of registrants, 3-B, was established. Into this class go those who have dependents and are also working at "necessary jobs in a critical occupation." The majority of draft boards did not make use of this classification until September, hence not too much information is available as to the kind of occupations included in this class by draft boards. It is known, however, that various boards in several "oil states" have placed geologists and geophysicists with dependents in 3-B. Much reclassification, particularly of registrants in 3-A, remains to be done by the local boards. Occupational Bulletin No. 15 lists the various "critical occupations" in the oil industry; hence "necessary men" are those employed in these occupations.

In the *Oil Weekly* of September 14, 1942, General Lewis B. Hershey advises the oil industry to take an inventory of its manpower and decide which employees are regarded as "necessary men." By inference he suggests that local boards should be advised of the names of men so regarded. Several corporations have already so classified their men and many others are in this process. Members who are "self-employed" (consulting geologists, etc.) have the same right to advise their local boards of their status, calling attention to Bulletin No. 15.

Oil, being one of the vital essentials of war, must be available at all times in ample quantities to our armed forces. Fortunately when we entered this war we had abundant quantities for our foreseeable needs both for the armed forces and civilian use. The fortunes of war change rapidly and what was an adequate supply at the time of Pearl Harbor may become inadequate within the near future. The need then for continuing the exploration for and exploitation of our oil fields will increase as our war effort grows.

It must at all times be borne in mind that Selective Service is not a system that is static but is constantly changing to meet the needs of army and civilian life. If you are thoroughly familiar with Selective Service and its rules today you will be obsolete in ninety days, if you do not follow closely the changes that are taking place.

PROCEDURE ON APPEAL FROM CLASSIFICATION OF LOCAL BOARD
(October 1, 1942)

1. Every registrant must be notified of his classification by the local board.
2. Every registrant must be notified of any change in classification.
3. Registrant, any member of his family or his employer have ten days in which to file a protest on the classification, and file an appeal which can either be based on dependency or on occupation, or both; the latter may require the filing of Form 42-A or 42-B giving complete information on the kind of work done by registrant.

4. Local board must review the case, including all new evidence which may be offered. In this connection the services of the appeal agent may be called for by the board (each local draft board has a Government appeal agent).
5. If the appeal is denied the local board must advise the registrant and the one appealing.
6. On the bottom of the form on which notice is sent of "Appeal Denied" (Form 59) there is printed a form which when filled out and returned to the local board advises them that you are taking an appeal from them to the *District Appeal Board*.
7. At its next meeting, following your notice, the *District Appeal Board* will examine the complete file of the registrant furnished by the local board. They can either affirm the decision of the local board or uphold the contention of the appellant and require the registrant to be placed in the class requested.
8. If the *District Appeal Board* affirms the decision of the local board, this decision is final if based on occupational reasons only. If the appeal involves the question of dependency, the appellant's request is sent to the State Director of Selective Service who may certify the case to the President for final consideration.

MEMORANDUM OF NATIONAL SERVICE COMMITTEE

National Roster of Scientific and Specialized Personnel

Comments on the National Roster have been included in memoranda and articles from time to time in the Bulletin of the A.A.P.G. by the National Service Committee. Your attention has been directed to the scope and policy of this organization. In order to fully coöperate with them and in order to have a complete file of questionnaires, an arrangement was made to re-circularize the membership of the A.A.P.G., accompanied by a letter of special appeal by F. L. Aurin, President. The primary intention of this arrangement was to appeal to those members who had not sent in the questionnaire sent out about a year ago, to comply with the request of the National Roster. There were several groups of forms: (1) "Originals" were sent to members who had not registered their skills with them; (2) "Re-circularizations" were forwarded to members who had returned original questionnaires, and were designed to bring up to date current information for their files with a minimum of effort on the part of the registrant. In the event there should be any duplication of questionnaires, it is urgently requested that you send in the duplicate information to the National Roster.

The members of the A.A.P.G., who have registered with the Roster have been very negligent in advising the Roster of any change in their Selective Service classification. This has been called to your attention before and you are again urged to comply with this request. The Roster has advised that the lack of this information may account for the great number of petroleum geologists having been drafted, and if their evaluating committee had possessed the correct information on the draft status of these individuals, it might have been possible to have arranged for a more full utilization of the talents of these individuals.

New Developments

There has been a request from a certain branch of the Government for the services of men who can qualify as follows:

"We need men who speak Spanish or Portuguese and with experience in Latin countries. We can use men with outside experience as, for example, foremen or superintendents of construction work, transportation, etc. We also need a few men in administration as heads of departments, etc."

It would appear that our membership includes a technical group whose services, if available, would be interested only in administration or in charge of group activities. It is possible that strategic materials might be involved and that men with a mining background could handle such assignments very well. Among the membership of the local geological societies there may be some non-technical men who could qualify for some of these services. All inquiries should be directed to F. L. Aurin, 1607 Trinity Building, Fort Worth, Texas.

There has been another request for geologists or mining engineers for services in Latin America. To qualify for these assignments, it is necessary that applicants have a rather broad background of mining experience. It would be very desirable to have a practical working knowledge of Spanish or Portuguese. All inquiries should be directed to F. L. Aurin, 1607 Trinity Building, Fort Worth, Texas.

Important New Change in Army Air Corps

It is our understanding that the new regulations in the Air Corps, prohibiting the granting of commissions to civilians except those having former commissions, have been modified to the extent that the Air Corps will now consider the applications of qualified civilians for commissioned officers as Interpreters of Aerial Photographs. The applications of those having applied through the Appointment and Procurement Section or through Lt. Col. Charles G. Morgan will be processed at an early date. It is also our understanding that new applications can be made at this time. In any event, those previously making applications and those doing so now should communicate with Lt. Col. Charles G. Morgan. This is really good and encouraging news to our membership, as many of them have previously made application for this type of work.

Encouraging progress is being made in several branches of service for the use of geologists as Geologists and Geological Engineers. We hope to be able to report definite information on this to the membership at an early date.

Rôle of the Petroleum Geologist and Geophysicist in New Exploration Work

As time goes on, the demand for geologists and geophysicists in military and civilian activities directly connected with the war effort is rapidly increasing, and the time may not be far distant when the petroleum industry will not be able to give up many more geologists and geophysicists. Some of the companies and other operators have already lost so much personnel that further depletion of their key men (both company and independent consulting) in both geological and geophysical activities will seriously handicap their exploration programs. Such situations must be avoided, as it is absolutely necessary for the petroleum industry to explore, prospect, and discover substantial new reserves. Such necessity is not confined to the United States, but is also applicable to other areas and countries strategically located where the discovery and utilization of petroleum in our war effort is essential. Senator O'Mahoney, chairman of the Sub-Committee of the Senate Public Lands Committee, after a recent hearing, stated: "The undisputed facts revealed by these hearings are that production of oil has been falling off, wildcatting, or the search for new fields, has nearly ceased, while the growing war demand may well deplete our known reserves, endanger the conservation policy, and in time, force us to turn to oil shale and coal for petroleum substitutes." The Office of Petroleum Coördinator for War, through Harold L. Ickes and others in his organization, has also repeatedly pointed out the fact that the downward trend of new discoveries and the present scarcity or dearth of new exploration and discoveries, has reached a critical stage, and that something in the way of a constructive program of coöperation and encouragement must be established to stimulate the exploration work for new fields. It is absolutely necessary that this program of new exploration be carried out in order to guarantee the fulfillment of the entire war effort. *We have the strongest hope and trust that it will be carried out.* When this program gets under way, it will tax the skill, ingenuity, imagination, and resourcefulness of all petroleum geologists and geophysicists, who will be the directors and have the responsibility of carrying out this important assignment to a successful conclusion. Then, as previously stated, the petroleum geologist and geophysicist must be left in a position to perform this duty. Even though these key men (both company and consulting), and the local draft boards in many cases, feel that their places are in the military service, yet they are just as patriotic and are doing a greater service to their country if permitted to stay in their present work and do their utmost to discover and develop new reserves.

The executive committee has announced that the twenty-eighth annual convention of the Association will be held in Fort Worth, Texas, April 7, 8, and 9, 1943. The convention headquarters hotel will be announced later. A. I. LEVORSEN is chairman of the program committee; he will be assisted by A. R. DENISON and KARL A. MYGDAL and the program will be built around the subject of secondary recoveries and new petroleum reserves. This will be the usual combined meeting of The American Association of Petroleum Geologists, the Society of Economic Paleontologists and Mineralogists, and the Society of Exploration Geophysicists.

DAN E. BOONE, formerly district geologist for the Houston area of the Halliburton Oil Well Cementing Company, is now general superintendent of the electrical well services department, for that company, in charge of personnel and equipment.

JAMES R. DAY is a second lieutenant, stationed with the Coast Artillery at Camp Tyson, Tennessee.

NOEL W. ENGEL, 122 Sherman Avenue, Hamilton, Ohio, is a lieutenant (j.g.) in the U. S. Naval Reserve.

BEN F. HAKE has accepted a commission with the Army engineers. His former company connection was the Gulf Refining Company at Indianapolis, Indiana.

Lieutenant HARRIS COX may be addressed in care of the Mail and Dispatch Section, Office of Naval Intelligence, Navy Department, Washington, D. C.

WILLIAM D. LEWIS reported for active duty at the Naval Training Station, Tucson, Arizona, in November.

Private KENNETH G. BOLING is with the 654th Engineers at Camp McCoy, Wisconsin, in training for photograph interpretation.

C. A. HEILAND, professor of geophysics at the Colorado School of Mines, Golden, spoke on "War Time Applications of Geophysics in Engineering Geology and Strategic Minerals Exploration" at the November 2 meeting of the Rocky Mountain Association of Petroleum Geologists, held in Denver.

New officers of the Indiana-Kentucky Geological Society are: president, RICHARD S. HICKLIN, Carter Oil Company; vice-president, CHARLES J. HOKE, Phillips Petroleum Company; secretary-treasurer, ROBERT F. EBERLE, The Superior Oil Company, all of Evansville, Indiana.

JACK L. HOUGH has been granted leave from the Humble Oil and Refining Company to accept a position as civilian scientist with the Bureau of Ordnance, Navy Department, in Washington, D. C., for the duration.

ROBERT F. EBERLE, formerly with the Tide Water Associated Oil Company, is now associated with the Superior Oil Company, 1004 Citizens National Bank Building, Evansville, Indiana.

Lieutenant KEITH M. HUSSEY is an instructor in the Ground School at the Midland Army Flying School, Midland, Texas.

JOSEPH D. TOMPKINS is a captain in the Ferrying Division of the Air Corps, Air Transport Command, Love Field, Texas.

The East Texas Geological Society elected new officers for 1943 as follows: president, E. B. WILSON, Sun Oil Company; vice-president, LAURENCE BRUNDALL, Shell Oil Company, Inc.; secretary-treasurer, B. W. ALLEN, Gulf Oil Corporation, all of Tyler, Texas.

ROBERT H. CUYLER is a first lieutenant in the Air Corps Pre-Flight School, San Antonio, Texas, in the Supervision Section, Department of Maps, Charts, and Aerial Photographs.

Lieutenant (j.g.) G. T. MCINTYRE, D-V (P), U.S.N.R., may be addressed at Room 22, Hollis, Naval Training School (Communications), Harvard University, Cambridge, Massachusetts.

TEXAS

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Gulf Oil Corporation

Meetings: Monthly and by call.
Luncheons: Every Monday at 12:00 noon, Blackstone Hotel.

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Regular meeting held every Thursday at noon (12 o'clock), Mezzanine floor, Texas State Hotel. For any particulars pertaining to the meetings write or call the secretary.

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Meetings: Third Tuesday of each month in San Antonio. Luncheon every Monday noon at Milam Cafeteria, San Antonio, and at Plaza Hotel, Corpus Christi.

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Luncheons and evening programs will be announced.

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Consulting Geologist, Box 707

Meetings will be announced

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Owens, Libbey-Owens Gas Department
4007 Staunton Ave., Charleston, W.Va.

Meetings: Second Monday, each month, except June, July, and August, at 6:30 P.M., Kanawha Hotel.

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SECOND EDITION

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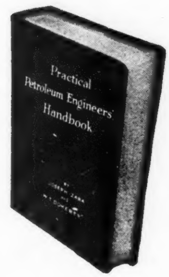

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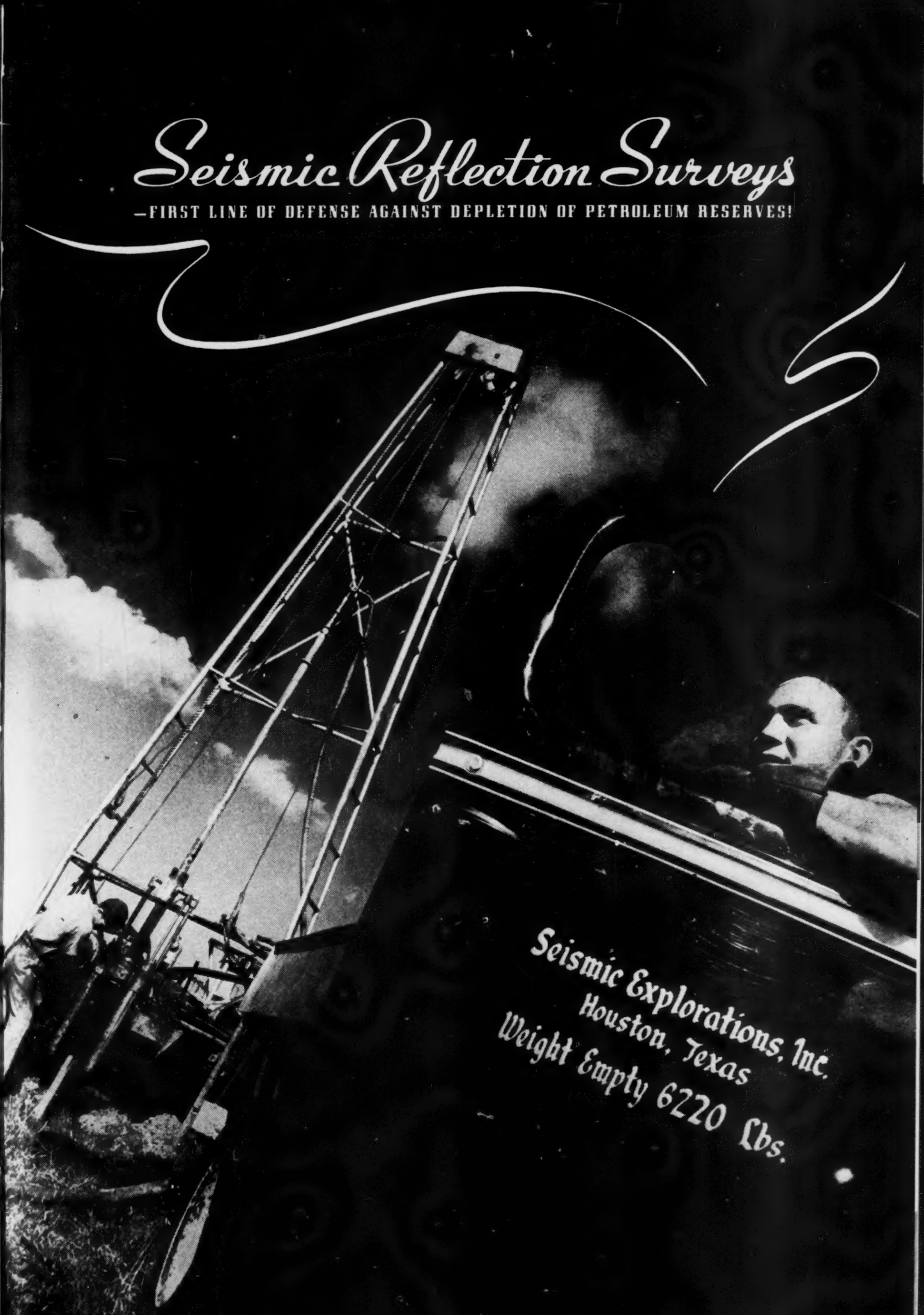

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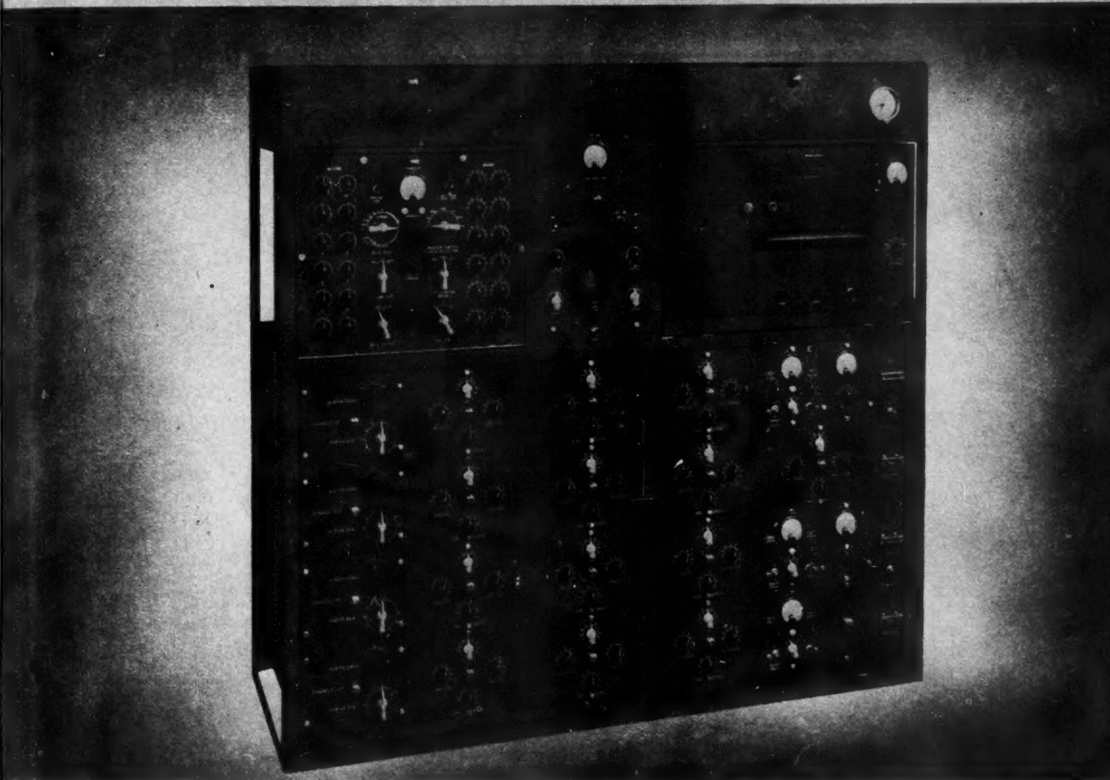

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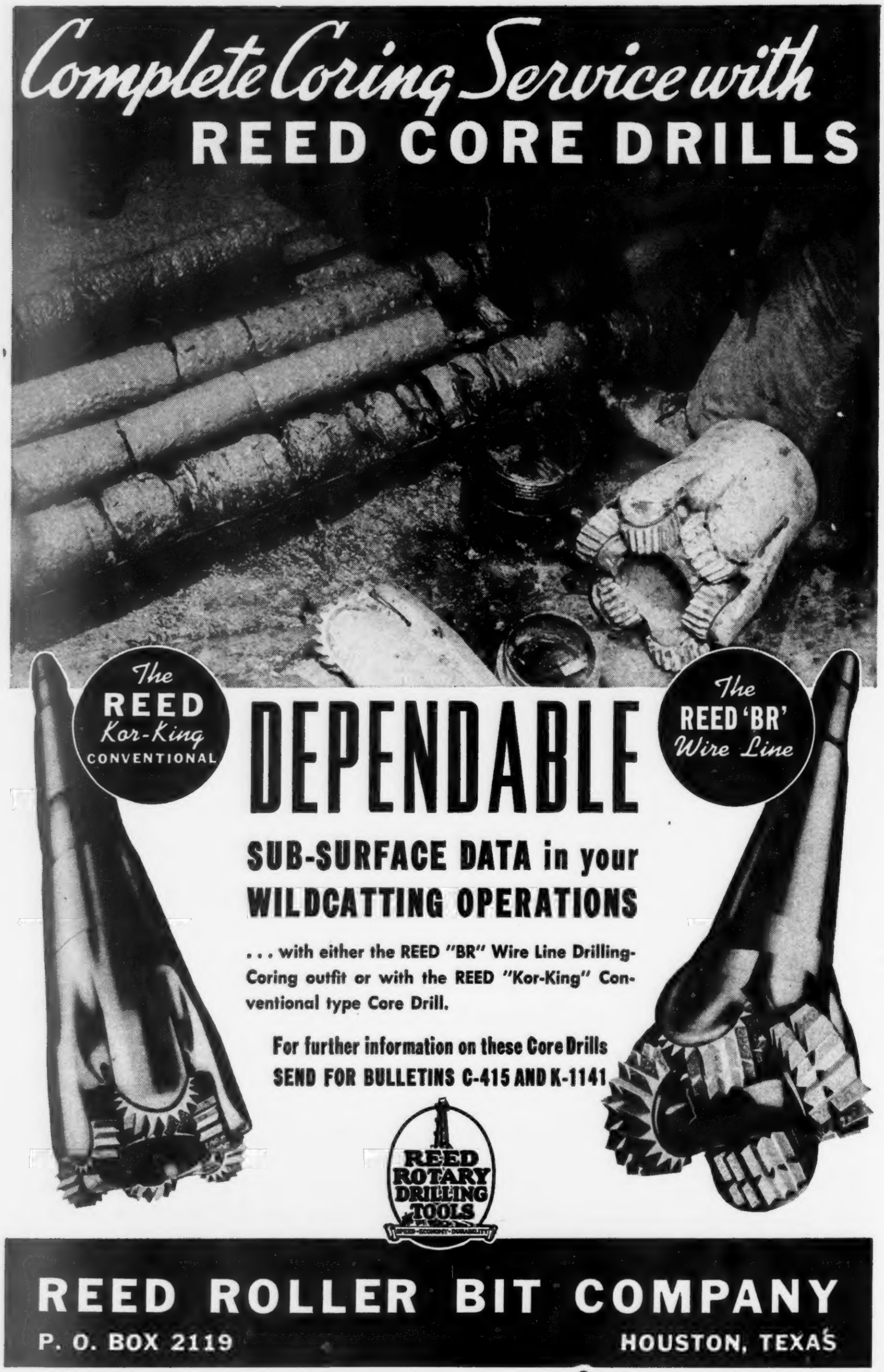
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